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THERMAL METHODS OF DEVELOPING PETROLEUM DEPOSITS

31 JULY 1979 (FOUO 28/79) 1 OF 2

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31 July 1979

USSR Report

RESOURCES

(FOUO 20/79)

Thermal Methods of Developing Petroleum Deposits

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THERMAL METHODS OF DEVELOPING PETROLEUM DEPOSITS

Moscow TEPLOVYYE METODY RAZRABOTKI NEFTYANYKH MESTOROZHDENIY in Russian 1977 signed to press 5 Sep 77 pp 13-27, 70-72, 83-126, 135-138, 193-230

[Part 1, Chapter 1, excerpt from Chapter 5, Chapter 7, Chapter 9; Part 2, Chapter 7 and Chapter 4 from book by N. K. Baybakov and A. R Garushev, Izdatel'stvo "Nedra", 2000 copies 238 pages]

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FUELS AND RELATED EQUIPMENT

THERMAL METHODS OF DEVELOPING PETROLEUM DEPOSITS

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[Text] PART 1. DEVELOPING PETROLEUM DEPOSITS WITH THE USE OF HEAT CARRIERS

CHAPTER 1. STAGES IN THE DEVELOPMENT AND PROSPECTS FOR THE USE OF THE THERMAL METHOD TO INCREASE OIL YIELD

For all their huge economic effectiveness and rapid recovery of capital investments, modern methods for developing petroleum deposits possess an essential flaw that consists of the fact that even under the most favorable conditions, as a rule the degree of bed output (oil yield) does not exceed 50 percent of the geological reserves. For many deposits the final oil yield ranges from 1 to 10 percent. Consequently, the struggle to increase petroleum recovery from beds is a most important national economic goal that should be solved by further improving the existing methods for acting on a bed (transcontour and contour flooding and others) and using fundamentally new methods based on both the study and utilization of a bed's natural peculiarities and the possibility of abruptly changing some of its properties (rock permeability, oil viscosity, phase composition of the hydrocarbons, and others) and working conditions.

A number of methods for increasing a bed's oil yield are known, but the most prevalent of all still remains the method of intensifying oil extraction by flooding the beds (transcontour, contour, focal, and so on).

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The scale of the use of bed-flooding has grown from year to year. For example, the use of this method is related to the extraction of about 70 percent of all the oil produced in this country. A further expansion of the volume of work done with flooding has been planned. Simultaneously with this, in order to increase the flushing capabilities of the water in the bed, thicken and increase the density of the displacing agent and so forth, measures have been worked out for the improvement of this method through the addition of different chemical reagents (PAV's [surface-active substance], carbon dioxide and others).

However, this still does not solve the problem of the rational use of the natural resources of petroleum deposits. This applies particularly to those deposits characterized by poor reservoir properties or heavy and viscous oil, where oil extraction efficiency is extremely low (10-20 percent). It is well known, for example, that in a number of fields in Krasnodarskiy Kray and the Ukrainian and Azerbaydzhan SSR's, among other places, oil extraction with the help of flooding has not yielded positive results in many cases.

When a cooled agent is injected into an oil-bearing bed containing paraffin-based oil, part of the bed's pores become clogged because of precipitation of the paraffin out of the oil. When this is done in oil pools containing highly viscous or tarry oil, there is an inrush of the injected agent and rapid inundation of the yield because of the mixture's high viscosity ratio. This situation is sharply aggravated in beds with a high degree of heterogeneity, as represented by fractured-pocket and porous reservoirs, where the effective use of flooding cannot be carried out successfully, for all practical purposes.

According to preliminary estimates, deposits of highly viscous oil are regarded as primary potential objects for the utilization of new development methods. These deposits include: Arlanskoye in Bashkiria, Usinskoye and Yaregoskoye in the Komi ASSR, Kenkiyak in Kazakhstan, Okha and Katangli on Sakhalin Island, and the Zybza-Glubokiy Yar in Krasnodarskiy Kray, as well as a number of others in that area that are confined to Miocene deposits.

Thus, increasing the oil yield factor by using new methods of acting on the bed has the same effect as discovering new fields.

The deposits mentioned are located in built-up regions where there are industrial and power-producing organizations, as well as water resources, housing and trained personnel. Therefore, work on increasing the oil yield of beds is most urgent in

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these areas. Particular attention should be given to the fact that additional oil can be obtained without the expenditures needed for the settlement and development of new oil regions.

Research performed primarily in the last 15-20 years has established that the final oil yield from the bed of most deposits that do not lend themselves to development by known methods depends on the bed's reservoir properties and the physicochemical characteristics of the oil itself. It has been determined that the artificial creation of thermohydrodynamic processes in a bed can have a significant effect on the mobility of the oil in an oil-bearing reservoir, and when the appropriate processes for thermal action on a bed are chosen, it is possible to achieve a substantial increase in the effectiveness of oil deposit development.

The idea of using a thermal factor for increasing the oil yield of beds and the development of facilities for this purpose belong to Soviet science. This is no accident, either. Views expressed by such leading figures of Soviet petroleum science as D.V. Golubyatnikov, I.M. Gubkin and A.D. Arkhangel'skiy should be regarded as the basis for the formulation of this idea.

In his study of the natural conditions governing the migration of petroleum and discussion of questions relating to the formation of accumulations of petroleum, I.M. Gubkin wrote: "The natural conditions for the movement (migration) of petroleum with respect to a bed create conditions analogous to the situation created by artificial heating.

"As the depth and (consequently) the temperature increase, the liquid can change into the vaporous and gaseous state, as a result of which there is a significant increase in the pressure in the bed, which forces the gas and oil to move along the line of least resistance." [18]

In these statements there is much that suggests the necessity of injecting heat carriers into a bed or using the natural thermal sources in the bowels of the earth in order to increase the effectiveness of the petroleum extraction process.

In evaluating the role and value of the geothermal observations first made by him in Surakhany and on Bibi-Eybat in 1916, D.V. Golubyatnikov noted the following: "In addition to the purely scientific interest, the measurement of temperatures in a borehole has another purpose, which is to elucidate questions of a practical nature, such as: the source of the influx of oil into the bottoms of wells and the role of fractures in this process, the use of temperature measurements in rock that does not

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contain oil and the temperature of oil flowing into well bottoms in order to study the geological profile of a deposit, as well as the relative positions of water- and oil-bearing strata and so forth." [16]

It is completely natural that these thoughts were further developed under those conditions created by Soviet science and technology in searching for more rational ways of working oil deposits.

In this respect we should point out that not only the general idea of using the thermal method to affect a bed, but also the determination of the separate technical spheres belong to the great Russian scientist D.I. Mendeleyev, the distinguished Soviet geologist I.M. Gubkin, L.S. Leybenzon, and others. As long ago as 1888, Mendeleyev considered that ". . .that epoch in coal extraction is beginning when coal will be transformed in the beds into gaseous fuel, and this gas will be sent to consumers to be used as fuel."

The concept of the underground gasification of coal, as expressed by D.I. Mendeleyev and supported by V.I. Lenin, has been reflected and continued in the solution of the question of the effect of heat on oil-bearing beds for the thermal intensification of oil extraction, particularly in the intrabed burning (VG) method.

The technological processes for the underground gasification of coal and the thermal intensification of oil extraction by the VG method have many common aspects. This underlines the continuity and definite trend in the development of ideas in this field by our native (Russian and Soviet) science.

Workers at the State Scientific Research Institute of Petroleum (GINI), in Moscow, were the first in world practice to come up with specific and substantiated proposals for testing and using the thermal method of acting on an oil-bearing bed. In the years 1931 and 1932, A.B. Sheynman, a worker at the institute, suggested that oil-bearing beds be subjected to a thermal effect and that different specific methods be tested for this purpose: igniting an oil-bearing bed and creating a moving focus of combustion inside it; the injection of hot gasses into a bed; the injection of a mixture of heated gasses and (atmospheric and reaction) water vapor into a bed; the creation at the well bottom of a permanent thermal source, and so on.

These methods were intended to cause a maximum increase in the oil yield of the beds in fields being exploited by primary methods and in depleted fields (that is, fields undergoing secondary development).

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In 1932, a group of scientific workers at GINI (A.B. Sheynman, K.K. Dubrovay, N.A. Sorokin, M.M. Charygin, and S.L. Zaks) conducted extensive laboratory investigations into the creation of a moving focus of combustion in an oil-bearing bed, the testing of various methods for igniting a bed, the effect of heated agents on a bed, and so on. Special experimental installations were built in order to do this research. Bed models were made in metal pipes with a volume of 5 m^3 that were filled with a packed sand mixture.

Models were built that simulated ignition and injection boreholes, operating wells, and combustion chambers under pressure, and monitoring instruments and other equipment were developed. These experiments, which were the first of their kind in the world and the results of which were observed by Academicians I.M. Gubkin and L.S. Leybenzon, M.V. Barinov, and G.I. Lomov, produced the first confirmation of the following facts:
1) an oil-bearing bed can be ignited;
2) combustion can be maintained in a bed by feeding air into it, while combustion in a bed is accompanied by a rise in the temperature in the bed to very high limits;
3) the focus of combustion can move along a bed from an ignition borehole to operating wells;
4) an immobile focus of combustion can also be maintained at the bottom of the ignition borehole;
5) a bed subjected to thermal treatment yields the maximum (almost all of its) oil.

A.B. Sheynman and K.K. Dubrovay[1] described these experiments. It should be mentioned that they were the first to introduce the term "thermal methods of extracting oil."

In the foreword to their book, Academician I.M. Gubkin wrote: "The proposed book discusses a question of extraordinary importance, the positive resolution of which can cause a complete revolution in the development of petroleum deposits."

The success of the experiments at GINI enabled the institute to propose the testing of the ideas under production conditions. Consent for this was given in an order from the USSR People's Commissariat of Heavy Industry that was signed by Comrade Ordzhonikidze.

---

[1]Sheynman, A.B., and Dubrovay, K.K., PODZEMNAYA GAZIFIKATSIYA NEFTYANYKH PLASTOV I TERMICHESKIY SPOSOB DOBYCHI NEFTI (Underground Gasification of Oil-Bearing Beds and the Thermal Method of Extracting Oil), Moscow, ONTI [Department of Scientific and Technical Information], USSR NKTP [People's Commissariat of the Fuel Industry], 1934, 96 pp.

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For the performance of this critical experiment, I.M. Gubkin suggested a section in the southern branch of the Neftegorskiy field (Krasnodarskiy Kray) that he knew well from his previous work, which was related to the discovery of the Maykopskiy oil deposits.

On the basis of this full-scale research, the results of these experiments made it possible to reach the following conclusions:
a) oil-bearing beds can be ignited, the bed will burn, and combustion can be maintained in it;
b) there are a number of methods for igniting a bed, the effectiveness of which has been tested;
c) gas and oil can be extracted from a depleted bed as the result of a thermal effect.

The extraction of the oil confirmed the preliminarily advanced hypothesis of the possibility of a thermal extraction method.

Academician I.M. Gubkin, who was present at Mayneft' during the experiments, wrote: "We have found the solution to a problem of the greatest practical importance."

The following are the evaluations the work of the Soviet scientists on thermal methods of extracting oil received in the foreign press.

In CRACKING -- ART, one of the review collections systematically published in the United States, the well-known American chemist and technologist Dr. Egloff gave his views on the question of the development of the oxidation cracking process in the Soviet Union. He thinks that, from the chemical-technological viewpoint, the intrabed burning process is a specific modification of oxidation cracking carried out under subterranean conditions. Dr. Egloff presents the "underground oxidation cracking" results obtained by the Soviet investigators and in connection with this (and not without good grounds for doing so) makes no reference to any American work, proposals, or patents in this field. He objectively mentions that the thermal method with an intrabed combustion focus is a variant of the oxidation cracking process suggested by Soviet scientists.

Thus, according to Egloff both oxidation cracking and the intrabed combustion focus are achievements of Soviet science.

In 1938-1939, the PETROLEUM ENGINEERS' JOURNAL printed a translation of an article from the magazine NEFTYANOYE KHOZYAYSTVO (Petroleum Management) on the work being done by Mayneft'. In connection with this there were also no indications that similar experiments had been or were being performed in the United States.

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In 1952, Dr. Walter (Ryul'), discussing in chronological order the history of secondary methods of extracting oil from 1929 to 1938, mentioned that in 1934 the injection into a bed of a heated mixture of gasses and air (at a temperature on the order of 500-600°C) was carried out in the Soviet Union, in the Maykopskiy oil fields, for the first time in the history of the development of secondary methods. Dr. Ryul' gave a detailed description of all the work done in this field in the Soviet Union and also listed the results that were obtained.

Historical references and further publications in the foreign technical literature confirm the unarguable priority of Soviet science in the field of the thermal method of extracting oil.

In the discussion of the problems of the thermal intensification of oil extraction, questions relating to understanding the rules governing the propagation of heat in a bed and -- in particular -- the area near the borehole's bottom are of great importance.

From their research, B.S. Grinenko, Ye.Ye. Krushel' and I.A. Charnyy propose solutions to the problem of the propagation of the thermal flow during the heating of the bottom zone of wells. Charnyy laid the foundation for analytical solutions of the problem of propagation of the heated zone in an oil-bearing bed during movement of the heat carrier. In connection with this he showed that the convective transfer of heat by a heat carrier takes place considerably more rapidly than heat propagation (by thermal conductivity) from a deep-lying stationary heat source.

Experiments in using steam for a thermal effect on a bed were conducted in 1953-1954 in oil fields in the Ukrainian SSR by E.B. Chekalyuk, A.N. Snarskiy and K.A. Oganov. They showed that steam at high pressures and hot water (the condensate of some part of the steam) have real industrial possibilities for intensifying oil extraction.

Subsequently, there was an increase in the amount of work done in the field of thermal methods of affecting a bed by Soviet investigators. N.A. Avdonin, G.Ye. Malofeyev, M.A. Bagirov, G.V. Vechkhayzer, Ya.A. Mustayev, I.M. Dzhamalov, and others continued to experiment, as a result of which the thermal method began to be introduced into practice.

Our proposed method for classifying thermal methods makes it possible to predict the development of this method with due consideration for the appearance of new achievements in the field of thermal engineering and physics. It is possible to conclude that the thermal method is a fundamentally new method

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for intensifying the extraction of oil that is distinguished by the fact that its operating principle is not only hydrodynamic, but also thermodynamic. While an isometric effect on the bed is used in the first case, in the second there arise such complicated conditions for affecting the bed that they effect not only a change in pressure, but also a change in temperature. Another fact that should be taken into consideration is that it is possible to produce deep phase or physicochemical changes in the mixture contained in the bed.

When a bed is acted upon by hot water heated by gasses or steam, conditions are created for phase changes of these components, as well as for changes in several of their physical and physicochemical properties. In connection with this we see distillation, evaporation, a lowering of viscosity, thermal expansion, a reduction in surface tension, degasification, and so forth. Even more radical transformations appear in connection with an intrabed focus of combustion. Cracking, pyrolysis, gasification, and -- finally -- high-temperature oxidation (burning) cause such profound changes in the state of the mixture in the bed that this method is unique among the other methods that have a thermal effect on a bed.

The methods of intrabed burning and acting on a bed with steam saturated with water have recently begun to be studied in foreign countries. In different areas of the United States, experiments have been performed to create VG and to use water vapor for practical purposes in areas with different geological features: bed depth, thickness, permeability, saturation, oil quality. During the implementation of VG, various methods of igniting the bed were used (air, oxygen, electric combustion chambers, coal packets). A summary of these methods is of considerable interest (see the classification of thermal methods on the page after next).

The clearest picture of the significance and prospects of VG as a method for completely exploiting oil-bearing deposits is shown in the works of Soviet investigators.

The use of VG to exploit a deposit completely was first done in the Pavlova Gora field (Krasnodarskiy Kray).

The gradual oxidation ("natural self-ignition") of the oil, under bed conditions, for 60-70 days after the beginning of air injection into the bed provided a thermal effect.

The process created in the bed of this field is characterized by three basic types of disturbances:
1) thermal (as the result of a supported intrabed oxidation

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process), characterized by an increase in temperatures for a series of wells from 21 to 200-400°C;
2) hydrodynamic (as the result of heat and mass exchange), which is coupled with an increase in pressure in the porous space of the bed;
3) operational, which abruptly increases the well flow rate and total oil output in a section by a factor of approximately 5.

The steam method of thermal action on a bed has been tested and is undergoing industrial development in another field in Krasnodarskiy Kray (in the Zybza area). This method was introduced into practice by the joint efforts of the Krasnodarneftegaz and KrasnodarNIPIneft' associations and the NGDU [Oil and Gas Production Administration] of Chernomorneft' [Association of the Black Sea Region Petroleum Industry].

Thus, the petroleum workers along the Kuban' River were some of the first in the Soviet Union to study and then introduce yet another variety of the thermal method of extracting oil. Their large-scale experiments (involving different ways of introducing the steam into the bed), observations of the effect of the process under different well state conditions, and the use of different monitoring methods produced materials that can be used in the further development of thermal steam methods of extracting oil.

At the present time, the thermal method in all its varieties has acquired independent importance in the technology for intensifying oil extraction. Some of its variants have been introduced into industrial production.

Let us present some technical and economic data that illustrate the effectiveness of the introduction of thermal methods in the oil extraction industry in the USSR.

For the period 1967-1976, about 6 million tons of oil were additionally produced because of the use of thermal treatments of wells and thermal actions on beds.

The prospects for the development of the thermal method, as a new direction in the technology of oil field development, are determined by the following criteria.

1. Imperfection of the existing methods for developing and exploiting wells.

2. The advantages of the thermal (thermodynamic) factor in comparison with the hydrodynamic factor and the proven effectiveness of some already developed methods for thermal action on a bed and the bottom zone in comparison with the usual methods.

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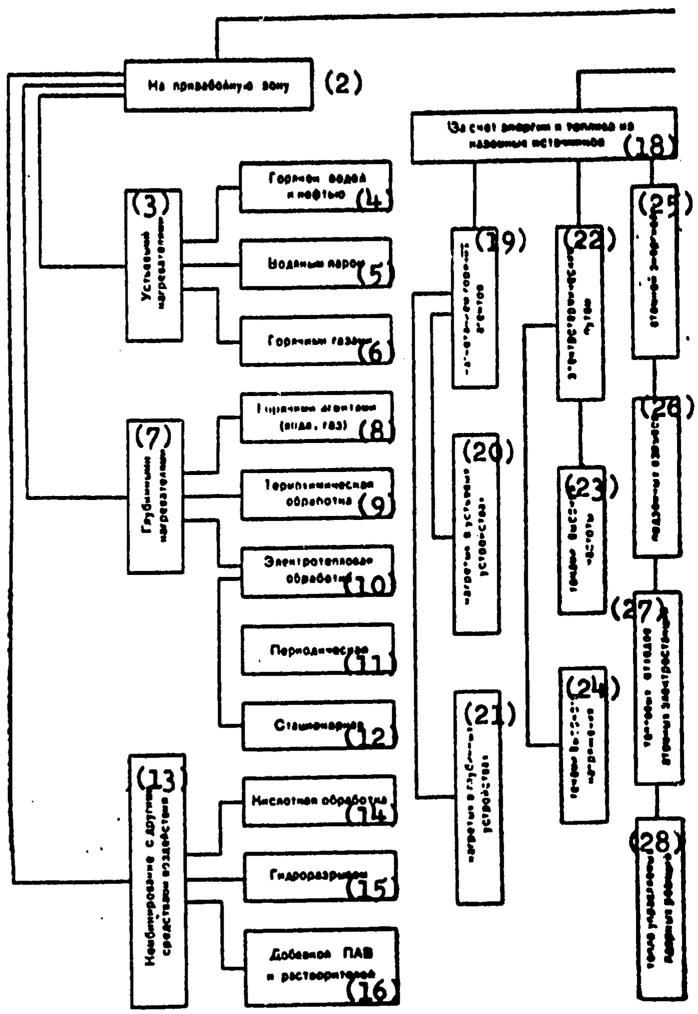
Classification of Thermal Methods



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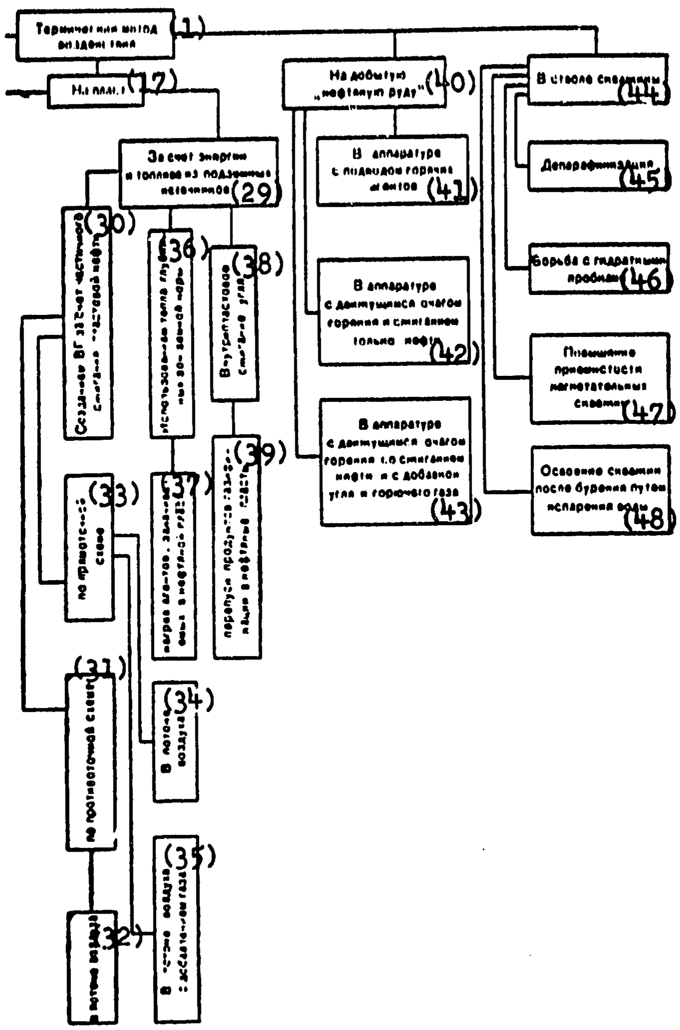

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Key to figure on preceding pages:

1. Thermal action method
2. On the zone near the bottom
3. With heaters at the well's mouth
4. Hot water and oil
5. Water vapor
6. Hot gasses
7. With deep-lying heaters
8. Hot agents (water, gas)
9. Thermochemical treatment
10. Electrothermal treatment
11. Periodic
12. Steady
13. Combined with other methods of action
14. Acid treatment
15. With hydraulic rupturing
16. With addition of PAV's and solvents
17. On the bed
18. Because of energy and fuel from surface sources
19. With injection of heated agents
20. Heated in well-mount units
21. Heated in deep-lying units
22. By electrothermal method
23. With high-frequency currents
24. With high-voltage currents
25. Atomic energy
26. Underground explosions
27. Thermal wastes from AES's
28. Heat from controlled nuclear reactions
29. Because of energy and fuel from underground sources
30. Creation of VG by partial combustion of oil in bed
31. By a counterflow method
32. In an air flow
33. By a direct flow method
34. In an air flow
35. In a current of air with gas added
36. Use of heat from deep zones in the Earth's crust
37. Heating of agents injected into the oil bed
38. Intrabed combustion of coal
39. Passage of gasification products into oil beds
40. On extracted "petroleum ore"
41. In equipment supplied with hot agents
42. In equipment with moving focus of combustion and burning of oil alone
43. In equipment with moving focus of combustion and burning of oil with added coal and hot gas
44. In well shaft
45. Deparaffinization
46. Action against hydrate locks
47. Increasing responsiveness of injection wells
48. Mastering wells after drilling, by the water evaporation method

3. The discrepancy between the accumulated (geological) reserves and the total amount of extracted oil (because of the existing low extraction factor), as well as the comparatively slow rate of increase in the extraction factor (coefficient of oil yield). As a result, as the surveyed reserves increase and as oil is extracted with due consideration for even increased oil yield coefficients, the amount of unextracted oil (residual reserves) increases from year to year. This creates an ever-growing stock for the use of improved methods for developing oil deposits.

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4. The diversity of the geography of the oil-producing regions, which is related to climatic conditions, the possibilities of obtaining water resources, the presence of permafrost, and so forth.

5. The variety and change in the stratigraphic distribution of productive horizons, depth of occurrence of the horizons, lithological characteristics, thermal conditions, and so forth. The necessity of insuring optimum thermal conditions during development has arisen. Previously this matter was not given the attention it deserved.

6. The change in the quality of the oil as new fields are discovered and developed. The reserves of heavy tarry, paraffin-based and asphalt-based oils are increasing.

7. The growth, development and radical improvement of equipment and methods for obtaining heat.

8. The technology of the thermal method.

The timely compilation of zoned production maps for the development of deposits (fields) by thermal methods, with an indication of the technically and economically substantiated specific and total energy consumption to insure the maximum oil extraction, will make it possible to plan the structures and sources needed to supply heat to fields marked for development by the thermal method.

9. The fundamental superiority of the mechanism of extracting oil by the thermal method over the hydrodynamic method ("cold" flooding).

In recent years there have been numerous meetings and seminars in which the workers of scientific research and planning and design organizations have participated, along with production workers, where work experiences and the results of scientific research and industrial experiments have been exchanged.

At the present time, thermal methods of acting on a bed are regarded as one of the basic directions for intensifying the extraction of oil and increasing the oil yield of beds for oil fields with different geological and technical characteristics at all stages of development. Considering the present state of the scientific research and -- in particular -- experimental industrial work to be still at the basic level, the Ministry of the Petroleum Industry, the USSR Council of Ministers' State Committee on Science and Technology, and the USSR Academy of Sciences have recommended that scientific research and experimental industrial work be done in the following areas.

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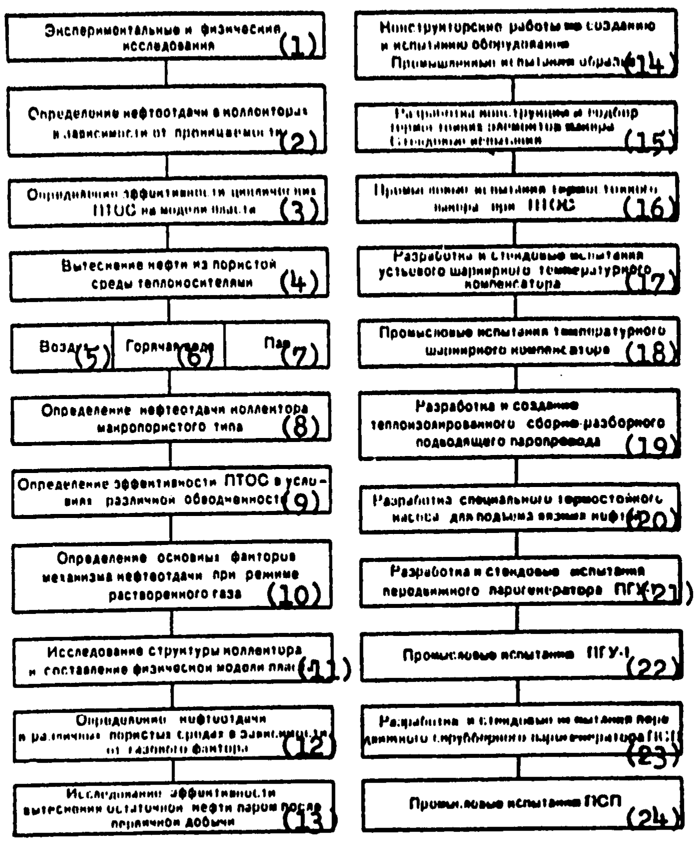
Complex of Projects to Insure the Effectiveness of Steam Methods of Acting on Oil-Bearing Beds Containing High-Viscosity Oil



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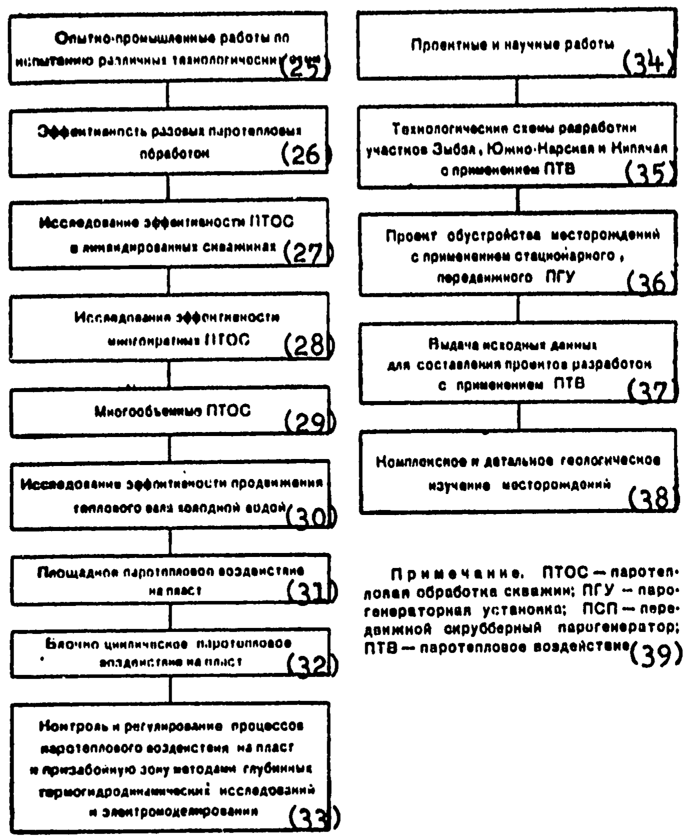

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Key to figure on preceding pages:

1. Experimental and physical research
2. Determination of oil yield in reservoirs as a function of permeability
3. Determination of effectiveness of cyclic PTOS on bed models
4. Displacement of oil from a porous medium by heat carriers
5. Air
6. Hot water
7. Steam
8. Determination of oil yield of macroporous-type reservoir
9. Determination of PTOS effectiveness under varying flooding conditions
10. Determination of basic factors of the oil yield mechanism under dissolved gas conditions
11. Investigation of reservoir structure and formulation of physical model of the bed
12. Determination of oil yield in different porous mediums as a function of the gas factor
13. Investigation of effectiveness of residual oil displacement by steam after primary extraction
14. Design projects for the building and testing of equipment; Industrial testing
15. Development of design and selection of heat-resistant elements of the packer
16. Industrial tests of heat-resistant packer during PTOS
20. Development of special heat-resistant pump for raising viscous oil
21. Development and stand testing of PGU-1 portable steam generator
22. Industrial testing of PGU-1
23. Development and stand testing of PSP portable scrubber steam generator
24. Industrial testing of PSP
25. Experimental industrial projects to test different processes
26. Effectiveness of one-time steam treatments
27. Investigation of PTOS effectiveness in abandoned wells
28. Investigation of effectiveness of multiple PTOS
29. High-volume PTOS
30. Investigation of effectiveness of advancement of heat front with cold water
31. Areal steam action on a bed
32. Cyclic-block steam action on a bed
33. Monitoring and control of steam processes for acting on a bed and the bottom zone by methods from deep thermohydrodynamic research and electric modeling
34. Planning and scientific projects
35. Production processes for development of the Zybza, Yuzhno-Karskaya and Kipyachaya sections, using PTV
36. Project for setting up oil field development using stationary and portable PGU's
37. Publication of initial data for compilation of development plans using PTV

[Key continued on next page]

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Continuation of key:
17. Development and stand testing of well-mouth articulated temperature compensator
18. Industrial testing of articulated temperature compensator
19. Development and building of thermally insulated, dismantleable steam feed line
38. Complex and detailed geological study of deposits
39. Note: PTOS -- steam treatment of wells; PGU -- steam-generating unit; PSP -- portable scrubber steam generator; PTV -- steam action

1. To consider the basic goal in the area of industrial introduction of thermal methods of developing oil fields in the next few years to be the introduction of the method of displacing oil with steam (in combination with flooding or without it) in deposits of heavy oil lying at shallow depths (up to 1,200 m), with primary emphasis on the following deposits: Katangli and Okha on Sakhalin Island, the Buzachi Peninsula and Kenkiyak in Kazakhstan, Yarega in the Komi ASSR, Zybza in Krasnodarskiy Kray, and deposits in Azerbaydzhan.

2. To achieve a significant expansion in the industrial testing of new combined methods for developing oil deposits by combining flooding and intrabed burning.

3. To expand the research work in the area of improving existing and creating new methods and production processes for developing oil fields, using thermal action on a bed, that will provide an improvement in the technical and economic indicators of the development process.

4. To achieve a significant expansion in work done to improve the technology of thermal action on a bed and the bottom zone.

The following must be done in order to achieve these goals:
the development of the technology and equipment for stationary heating;
the development of the technology for cyclic steam action under the conditions encountered in different reservoirs;
industrial testing of the effect of steam action in a fractured porous reservoir;
the development of technology to assimilate operating wells from the stock of inactive and test wells where no oil flow has been obtained by use of existing methods;
the creation of new and highly efficient methods (technological processes) of thermal action and the improvement of existing ones by combining them with other methods;
the development of a standard technique for determining the

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economic effectiveness of different methods of acting on the zone near the bottom of a well;
substantiation of the necessity of changing the wholesale price of gas and oil used as fuel for the production of steam (for injection into a bed);
the organization of the production of steam-generating units operating on gaseous fuel and nuclear reactors, which are more productive and promising and are needed for the development of large fields;
the development and support of the series production of the equipment needed to implement thermal action on a bed and the bottom zone of a well (self-compensating fittings, heat-resistant packers, pipes with thermally insulated surfaces, and so on);
the building of instruments and equipment to determine parameters and control production processes during thermal action on a bed and a bottom zone.

After the first steam treatments in our country were carried out in fields in Krasnodarskiy Kray (in 1965) and positive results were obtained, the initiative of the Krasnodarneftegaz association was approved. For the further development of this fundamentally new method of increasing oil yield, the Zybza field was assigned to an experimental organization for the conduct of experimental industrial work on steam effects on a bed on a broader scale. The investigations that have been carried out and the correlation of the results obtained will make it possible to use this work in other oil regions in this country.

In the period from 1965 to 1975, different technological variants of the steam effect were tested and laboratory research on the displacement of oil by various heat carriers was performed (see diagram on preceding pages). Portable steam-generating units that proved to be economical, transportable and easy to use were developed and built in collaboration with the Nal'chik Machine Building Plant and tested at the Zybza deposit. In addition to this, special well-bottom and well-mouth devices, without which the high-temperature process could not be implemented, were developed and manufactured directly in workshops in the field.

The first plan for the industrial development of the steam effect on a broad scale, using stationary steam-generating equipment, was prepared and went into effect at the end of 1969.

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CHAPTER 5. THE USE OF THERMAL METHODS OF DEVELOPMENT IN THE ZYBZA DEPOSIT OF HIGH-VISCOSITY OIL

[Excerpts] Oil Yield of Deposits With Micro- and Macroporous Reservoirs

Against a background of filtration characteristics and the mechanism of the oil yield of viscoelastic systems, one matter of both scientific and practical interest is a study of the development of specific deposits, with an analysis of the effectiveness of the use of different methods for acting on the bed and geological engineering measures instituted for the purpose of increasing the bed's oil yield.

From this viewpoint, many fields and deposits are of interest. However, in view of the experimental industrial work done on the effect of steam on a bed and intrabed burning at the Zybza deposit, let us briefly discuss the previous history of the development of this field before the use of thermal methods, allowing for the fact that this field is a typical analog of many deposits of high-viscosity oil.

As the result of the presence of two types of reservoirs and different compositions of the rock within the limits of the horizons where the Type II (macroporous) reservoirs are located, it is possible to distinguish highly productive zones that are the basic source (more than 90 percent) for the extraction of the high-viscosity oil. In the horizons where the Type I (microporous) reservoirs are located there are only slightly productive zones where the well yields are low.

Investigations have established that the oil in this deposit has viscoelastic properties. In connection with the latent energy of a viscoelastic system, the presence of a highly permeable Type II reservoir saturated with this oil made a definite impression on the nature of the field's development.

The development of the viscoelastic oil deposit in the Zybza section began in 1947. During the entire period of development

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the total oil yield was 9.3 million tons. Drilling was done in a triangular network with a distance of 100 m between the wells, although in the central part the distance between wells was 50 m. About 300 wells were drilled from 1947 to 1951, although no more than 230 wells were in operation at any one time, even in the first years of exploitation, since many of them were completely flooded in their first months of operation and were abandoned.

The development of this Miocene deposit of high-viscosity oil can be divided into four periods.

Period I (from the beginning of 1947 to September 1950) was characterized by an intensive increase in the rate of oil extraction because a large number of wells went into operation. The oil production rate increased from 50 to 4,920 tons per day, with the number of operating exploitation wells reaching 288. The total oil yield was 2.814 million tons. The output's water content did not exceed 8.8 percent and the rate at which it increased was insignificant (3.5 percent per year, at most).

Limiting the removal of liquid from the wells was an effective measure for reducing the water content of their output and prolonging their service life.

Period II (September 1950-October 1951) was characterized by relative stabilization of the oil extraction, with an insignificant reduction in it toward the end of the period. The drilling of wells continued, primarily in the thickening network in the central part of the section. The total number of operating wells ranged from 212 to 220. The total liquid yield was 1.875 million tons, which included 1.704 million tons of oil. At this stage the water content of the output did not exceed 12 percent, although it kept increasing gradually toward the end of the period.

Period III (October 1951-December 1957) was characterized by a rapid drop in average daily oil production from 4,200 to 200 tons, a further reduction in formation pressure (down to 7.5 kg/cm^2), intensive flooding of the deposit (up to 76 percent), and a reduction in the number of operating wells from 228 to 132.

Measures instituted to regulate the development of this Miocene deposit (limitation of the removal of oil by the existing network of wells and drilling in the Sarmatian deposits in the central and more productive area) did not stabilize the rate of the drop in formation pressure.

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In order to maintain the formation pressure, air injection was begun in August 1951, followed by gas injection into the elevated (head) part of the deposit. When the gas was injected, it rapidly broke through to the bottoms of the operating wells. Since gas injection did not change the rate of formation pressure decrease and did not result in an increase in the oil extraction rate, it began to be limited in September 1951 and was then completely halted.

Water began to be injected into the deposit, through eight injection wells located around its periphery, in 1952. At first the total amount of water injected was up to 3,100 m^3/day, although it later dropped to 800 m^3/day. In connection with this, the presence of a macroporous reservoir eliminated frontal displacement of the oil in the bed.

In order to further study the effect of injected water on the oil yield of a deposit, the injection of the agent was temporarily stopped several times, for periods of 1 to 6 months. During these cessations flooding stopped in most of the wells, the total oil yield was stabilized, and oil again began to be obtained from a number of completely flooded wells.

Despite the fact that the water injection period was characterized by a slower decrease in formation pressure in comparison with the preinjection period, there was no equalizing of formation pressure or intensification of oil extraction.

The total yield for the 6 years of this period was: oil -- 3.8 million tons; liquid -- 7.151 million tons.

Period IV (January 1958-August 1965) continued to the beginning of the experimental industrial work on the effect of steam on the bed.

During this period (7 years), oil extraction from the deposit continued to drop, from 200 to 86 tons per day, although the rate of decrease was much less than during the third period. The amount of water injected into the bed was gradually reduced (to 160 m^3/day), and at the end of 1960 the injection of water into the bed was halted. In connection with the reduction in the oil flow rate, the water content of the output increased, reaching 86-88 percent at the end of the period as opposed to the 76 percent content seen at the end of 1957. The total volume of water pumped into the deposit was about 2.5 million m^3. Because of the continuing flooding of the output, the number of operating wells was reduced to 98. Draining of the deposit during the last stage of its development continues to be carried out extremely unevenly, which is indicated by the current

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average daily oil and water yields, as differentiated by horizons.

By the end of the period of deposit development that is being discussed, the current oil yield rates from the operating wells ranged from 60 kg per day (wells 56, 30 and others) to 7-9 tons per day (well 373).

The graph in Figure 3 [not shown] shows the change in liquid and oil extraction during the development of the Zybza field. As is obvious from the data that have been presented, during a brief period (1.5-2 years) there was a rapid increase in oil extraction followed by a decrease in the yield at the same rate, despite the continuing increase in the number of wells drilled and put into operation. The abrupt rise and drop in oil extraction are reminiscent of a "splash," which is primarily related to the draining of the highly permeable macroporous reservoir, which had -- as was determined by laboratory and field research -- a high oil yield rate that reached 60-75 percent. Thus, during the period when work was done on the thermal intensification of oil extraction, almost all the oil was obtained because of the energy of the gas dissolved in it. The microporous-type reservoir remained almost undeveloped and, by analogy with deposits confined entirely to porous-type reservoirs, its oil yield apparently did not exceed 5 percent.

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CHAPTER 7. EXPERIMENTAL INDUSTRIAL PROJECTS AND THE RESULTS OF USING DIFFERENT TECHNOLOGICAL PROCESSES FOR STEAM ACTION ON A BED

[Text] Stages in the Development of Steam Action on a Bed

More than 10 years have passed since the first steam treatment of a well in the Soviet Union, which was performed in the Zybza field [27,31]. During this time, much complicated work has been done to determine the most effective technological processes that provide the highest final oil yield from a bed.

The work done in this field can be divided into the following stages.

Stage 1. Research work to determine the effectiveness of steam action (PTV) on a bed, using stationary industrial and portable boiler-type PPU-3M steam generating units and other equipment installed inside the well and on the surface as steam sources.

As the result of several PTOS's [steam treatment of a well] that were performed during this period, the effectiveness of the method was proven convincingly. There arose a need for the creation of special equipment that was easy to operate and, at the same time, met the requirements for conducting a PTOS.

Stage 2. Research and development of special steam generators and other equipment (heat-resistant packers, well-mouth temperature elongation compensators, recording instruments, and so on) made it possible to expand the scale of the work and sharply increase the effectiveness of PTOS.

In this period, the Nal'chik Machine Building Plant cooperated in manufacturing and testing the PGU-1 and PGU-2 portable steam generating units, with the following parameters: $p = 100$ kg/cm^2; $N = 3$-3.5 tons/hr of steam; $t = 200$°C. Following this, there was the development, manufacturing and testing under industrial conditions of the more productive PSP (portable

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scrubber-type steam generator), which has the following parameters: $p = 60\ kg/cm^2$; $N = 5.5$-6 tons/hr of steam; $t = 220^{\circ}C$. After that, the collective developed a normal series of steam generators that produce from 5 to 25 tons/hr of steam.

In conjunction with SevKavNIPI and then with the Kazan' branch of Azinmash [Azerbaydzhan Scientific Research Institute of Petroleum Machinery], heat-resistant packers were developed and used. At the same time, articulated temperature elongation compensators and dismantleable (quick-change) surface steam lines with high-quality thermal insulation were developed and tested under field conditions.

The use of heat-resistant packers and temperature compensators created the possibility of protecting the operating string from destruction because of high temperatures and, along with this, contributed to a reduction in the heat losses along the well's shaft through the creation of an air screen in the annular space. On the whole, the introduction of the complex of equipment mentioned above increased the reliability of the work being done and also made it possible to carry out PTOS with greater effectiveness.

The first steam generators and equipment for steam action on a bed were presented in a monograph published in 1971 [31].

Stage 3. This stage was characterized by an improvement in PTOS materiel and technology and an expansion of the goals of the thermal intensification of oil extraction, allowing for the transition from local treatment of wells to the treatment of large sections (blocks) of a field for the purpose of sharply increasing the bed's final oil yield.

The following questions were discussed and subjected to practical investigation:
1) criteria for selecting wells for steam treatment;
2) the effect on the degree of flooding on the effectiveness of PTOS;
3) optimum amounts of agent to be fed into the bed and the degree of heating of the area of the bed near the well bottom;
4) the effectiveness of repeated PTOS's;
5) the effectiveness of PTOS when used on wells abandoned because of low productivity or the absence of an oil flow;
6) the possibility of carrying out continuous, areal steam treatment of a bed under conditions of increased geological heterogeneity in the bed;
7) the possibility of moving the edge of the column of steam with cold water.

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During this period more than 200 well treatments were performed under varying geological conditions, with more than 100,000 tons of oil being recovered from the wells that were treated. Good results were obtained from abandoned wells, which yielded an additional 40,000 tons of oil. During the use of PTOS, the average yield per well treatment was 850 tons of additional oil, while the yield from abandoned wells was more than 1,000 tons. In determining the effectiveness of PTOS, as a rule all the wells were taken into consideration, including the so-called "unaffected" ones from which, for various reasons not related to the PTOS method, negative results were obtained.

Although additional oil was not obtained from a certain number of wells (on the order of 70) that were then assigned to the ranks of unaffected ones, the results obtained nevertheless gave us valuable material that made it possible not only to improve the technology of and equipment for steam treatments and determine the further prospects of the process of steam action on a bed, but also raised new problems. These problems were primarily related to the study of the geological structure of a deposit and the lithological characteristics of the reservoir.

Stage 4. This stage was characterized by further development of the process of steam treatment of a bed, on the basis of the powerful group of steam generating units that had been created.

At Zybza, the stationary boiler unit that was built, with three boilers of the KDVR-10-39 type and the necessary system of steam lines, made it possible to switch the supply of heat carrier from the boiler unit to any well in the area.

General views of the boiler unit and the layout of the steam supply lines are shown in Figure 21.

In addition to this, assembly work was completed on two semi-stationary steam generators built by the firm Takuma Boiler (Japan), which were used to inject steam in zones with low bed permeability and high formation pressures. The installed capacity of these steam generators alone was 45 tons/hr of steam, which figure reached 50-55 tons/hr when the portable PGU and PSP units were taken into consideration.

Together with the provision of productive capacities for steam injection into a bed, the fourth stage was characterized by an integrated study of deposits of high-viscosity oil and the selection of projects for thermal action on a bed in different parts of a deposit. At this stage, along with the creation of reliable equipment to insure a steady supply of heat carrier, objects (sections) were prepared not only for the injection of

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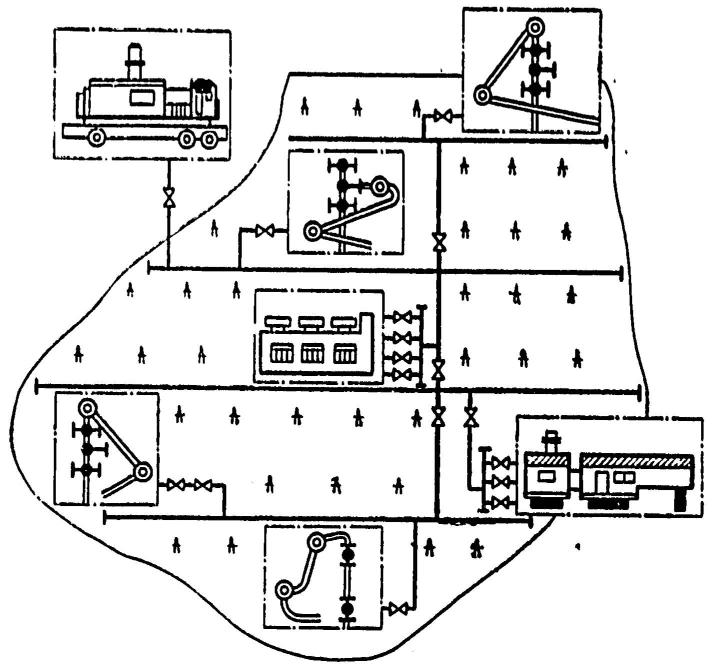

Figure 21. Process flow diagram of the setup for steam treatment of a bed at the Zybza oil field.

steam, but also for exploitation of the corresponding wells. However, in connection with the fact that a large number of producing wells (about 40 percent of the total number) went out of commission for various reasons, there arose difficulties related to the implementation of one production process or another. Although a small number of wells were successfully restored to operation, their spacing was still extremely unsatisfactory for the implementation of the production process and its regulation on the scale of the entire deposit.

Stage 5. The significant factor in this stage is the correlation of the extensive field material on the development of a deposit of high-viscosity oil both before and after the use of PTOS and PTV on the bed. An integrated study of the factual material is being conducted, the physicochemical and structural-mechanical properties of oil are being investigated, thermohydrodynamic observations are being made in wells, and a more thorough and detailed study is being made of reservoir lithology, as a result of which the existence of a new, anomalously permeable, void-type reservoir has been established. The

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discovery of this type of reservoir, which has a certain amount of subsidiary significance apart from its porosity, raises a number of serious problems, both in the area of searching for and surveying deposits with reservoirs of this type and in opening them up and setting up wells, using the appropriate equipment to accomplish this efficiently. Finally, there has been a completely new solution to the problems of evaluating and calculating geological and extractable reserves of oil, and the development of deposits has been carried out from the very beginning with the use of one of the PTV method of acting on the bed as the main means of increasing the oil yield.

The first technological process for developing the Zybza deposit and acting on the bed with the use of PTOS and cyclic-block PTV was formulated and introduced with due consideration for some of the special features mentioned above and a study of oil field development materials gathered in recent years, as well as theoretical research that has been carried out.

Effectiveness of Steam Treatments as a Function of the Output's Water Content

In view of the fact that beds are represented by both macro- and microporous reservoirs, a search was made for the final choice of a steam method for acting on a bed and for the optimization of the process as a whole. It was necessary to answer the following questions: what is the effectiveness of periodic (cyclic) steam treatments of wells; should there be protracted or continuous injection of steam into a bed under different physical geological conditions; what is the effectiveness of repeated thermal treatments of wells; is it possible to extract the remaining oil from a flooded bed, and so on.

Cyclic steam treatments of wells were performed during the first stage over a rather protracted period of time. From 1965 to 1969 alone, more than 200 such treatments were carried out. The technical and economic indicators of the steam treatments are presented in Table 14.

As a rule, the subjects chosen for steam treatment were low-yield or abandoned wells that, after having been injected with steam (1,000-1,500 tons of steam that increased the bed temperature to 120-150°C), were put back into operation with increased yields. The steam treatment method proved to be most practicable and costs were quickly recovered. Therefore, the thermal intensification method found widespread support among producers.

During the performance of this work, the basic goal was to find the optimum variant of the method of steam treatment of a bed that would guarantee a high final oil yield.

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Table 14. Technical and Economy Indicators of Steam Treatments

(1) Годы	(2) Число всех ПТОС	(3) Эффективные ПТОС	(4) ПТОС, оказавшиеся неэффективными по геолого-техническим причинам	Расход пара на все ПТОС (5)		Расход пара за год на эффективные ПТОС, тыс. т (8)	
				за год, тыс. т (6)	на одну ПТОС, т (7)	за год (9)	по нарастанию (10)
1965	3	2	1	3,1	1000	2	2
1966	31	15	16	30,7	1000	15	17
1967	37	24	13	42,7	1140	26,9	43,9
1968	40	25	15	55,4	1880	34,5	78,4
1969	25	16	9	37,6	1500	24	102,4
1970	53	35	18	69,1	1310	46	148,4
1971	40	23	17	39,5	990	22,9	171,3
1972	26	19	7	21	1000	19	190,3

Key:
1. Year
2. Number of all PTOS's
3. Effective PTOS's
4. PTOS's that proved to be ineffective for geological and technical reasons
5. Steam consumed for all PTOS's
6. Per year, tons x 1,000
7. Per PTOS, tons
8. Steam consumed per year for effective PTOS's, tons x 1,000
9. Per year
10. Cumulative
11. Additionally extracted oil, tons x 1,000
12. Cumulative additionally extracted oil, tons x 1,000
13. Average annual steam-oil factor, tons/ton
14. Allowing for abandoned unaffected wells
15. For affected wells
16. Additionally extracted oil per effective PTOS, tons
17. Commercial cost per ton of oil, rubles
18. Cost of additionally extracted oil, rubles

On the basis of field research, the dependence of the effectiveness of PTOS on the water content of the extracted output was determined, as well as the water content of additionally extracted oil as a function of the increase in the bed's temperature. It was established that good results can be obtained from wells with an insignificant water content in the output -- up to 30 percent providing that the temperature in the area of the well bottom is increased to 120°C. During the experimental period, up to 3 tons of steam were consumed per ton of additionally extracted oil. For wells with a high degree of output water content, 5-7 tons of steam were needed for each ton of additionally extracted oil (about 65 kg of gas were consumed to produce 1 ton of steam). At this stage, a steam-oil factor of up to 5-7 tons/ton should be considered economically justifiable when hydrocarbon fuel is used.

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Дополнительно добытая нефть, тыс. т (11)	Дополнительно добытая нефть по нарастанию, тыс. т (12)	Среднегодовой паронефтяной фактор, т/т (13)		Дополнительно добытая нефть на одну эффективную ПТОС, т (16)	Промысловая себестоимость 1 т нефти, руб. (17)	Себестоимость дополнительно добытой нефти, руб. (18)
		с учетом бросовых неэффективных скважин (14)	по эффективным скважинам (15)			
0,2	0,2	15,5	10	100		
4,0	4,2	7,7	4,1	450	9—82	15—50
14,0	18,4	2,98	2,4	750	9—36	6—39
20,2	38,6	2,74	2,1	800	10—53	4—23
25,5	64,1	1,47	1,6	1600	10—94	3—31
19,3	83,4	3,58	1,7	550	11—44	4—20
13,8	97,2	2,86	1,6	700	13—14	4—10
19,8	117,0	2,5	1,6	1000	14—20	4—15

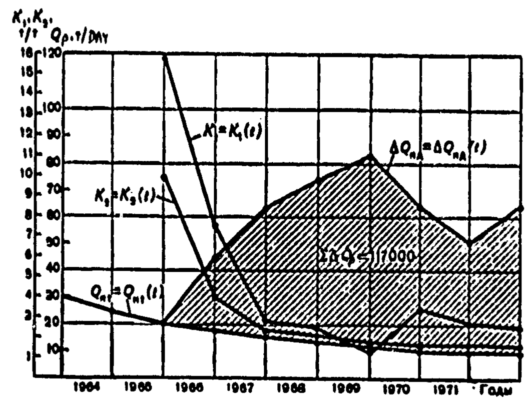

Figure 22. Dynamics of oil additionally extracted because of the use of PTOS. Allowing for PTOS: K_1 = unaffected; K_2 = affected.

As a rule, when wells were selected and all the technological requirements for the implementation of PTOS were observed, very good results were obtained. Figure 22 shows the results of PTOS for wells where all the conditions stipulated for PTOS were observed. PTOS was highly effective at all the wells where the requirements for it were met.

Careful investigations established that almost all the unsuccessful treatments were not related to the essential nature of the thermal effect. Primarily, the reasons for low efficiency were:

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1) an unfortunate choice of wells (wells with a high water content in the output, many of which were located beyond the limit of the oil-bearing area);
2) physical-lithological conditions of the reservoir (complex reservoir properties of the bed and the treatment of wells represented by clayey beds with insignificant streak interlayers or with very low oil saturation and permeability);
3) an inadequate degree of heating of the bed in the zone at the bottom of the well;
4) outbreak of the heat carrier through highly permeable macroporous reservoirs into nearby wells and the impossibility of insuring envelopment of the oil-saturated microporous reservoirs by the heat carrier;
5) technical causes (breaking of the casing string, seizing of the packer and so on);
6) a lack of reliable means for monitoring adherence to the production process and accounting for the feeding of heat into the bed;
7) a discrepancy between the amount of heat carrier (steam condensate) injected into the bed and the amount of liquid removed, which led to "flooding" and a decline in the flow of oil from the porous blocks because of the creation of counterpressure in the bed and an increase in the percentage of water in the output.

The causes of low PTOS efficiency for all the wells have been correlated and are presented below:

	Number of Well Treatments
Inadequate degree of bed heating.	35
Destruction of casing string.	16
Abandoned wells that proved to be in a water-bearing zone outside the oil-bearing area	10
Wells with clayey interlayers of oil-bearing streaks, low oil saturation and poor permeability.	14
Outbreak of heat carrier through highly permeable macroporous reservoirs, a low degree of heating and the impossibility of insuring envelopment of oil-saturated microporous reservoirs.	21

As is obvious from the data that have been presented, ineffective treatments were largely the result of incorrect selections of wells, technical complications and nonobservance of the technological conditions for PTOS.

Through numerous field and laboratory investigations it has been established that when wells are chosen correctly, the best results are obtained when the bed's temperature is raised to at least 120°C. Depending on the reservoir's properties and the

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revealed thickness and degree of flooding of the bed, it is necessary to feed in from 1,000 to 1,500 tons of steam in order to raise the temperature. It has been established empirically that, given the conditions listed above, it is necessary to feed in 70-100 tons of steam per meter of effective thickness of the bed.

High flow rates ranging from 5 to 15 tons/day, as opposed to 0.1-0.5 tons/day before the treatment, were obtained from most of the wells after PTOS. The period of effective operation of the wells ranged from 60 to 500 days, or even longer in individual cases. For examples, for 20 wells this period was 60 days; for 21 wells -- 125 days; for 31 wells -- 280 days; for 35 wells -- 500 days or more. The total flow rate of all the wells subjected to PTOS was barely 20 tons/day before the treatment.

Figure 22 shows the dynamics of the change in oil extraction for the list of wells given above, as well as the amount of additional oil extracted before and after the treatments. Without the steam treatments, operation of these wells would have been unprofitable as far back as 1966-1967.

Although many of the wells with macroporous reservoirs turned out to be unaffected because of the outbreak of the steam condensate through them, additional oil was still produced because of the reaction of neighboring wells. Therefore, these reacting wells were taken into consideration in determining the effectiveness of PTOS.

On the whole, as a result of the good communication between wells because of the presence of macroporous reservoirs, adjacent wells reacted during the period when the mass steam treatments were being carried out. More than 40 percent of the additional oil was obtained from these wells. Thanks to the use of PTOS, the running daily yield increased sharply and, at certain times, reached 100 and even 140 tons/day from treated wells. On the average, 845 tons of oil was extracted from a single treated and affected well, while in individual years this figure reached 1,600 tons. The amount of steam consumed per ton of additionally extracted oil (the steam-oil factor, or PNF) dropped from 10 to 1.6 tons/ton.

The water content of the output from treated wells did not exceed 50 percent, and in absolute figures it ranged from 0.1 to 10 tons/day. In individual cases, the output's water content reached 75 percent.

However, the effectiveness of the treatment of these wells depended primarily not on the percentage content of water in the

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Table 15. PTOS Effectiveness Under Conditions of Varying Water Content of the Output

Число ПТОС (1)	Расход пара, т (2)	Содержание воды до ПТОС, т/сут (3)	Дополнительно добытая нефть, т (4)	Паронефтяной фактор K, т/т (5)	Дополнительно добытая нефть на одну обработку, т (6)
25	28 500	0,0—0,5	31,500	0,98	1250
36	40 800	0,5—2,0	38,000	1,1	950
31	35 000	2,0—5,0	21,000	1,65	650
52	58 000	5,0—10,0	21,000	2,7	400
15	18 000	10,0 и выше (7)	5,500	3,3	350

Key:
1. Number of PTOS's
2. Steam consumed, tons
3. Water content before PTOS, tons/day
4. Additionally extracted oil, tons
5. Steam-oil factor K, tons/ton
6. Additional extracted oil per treatment, tons
7. 10.0 and more

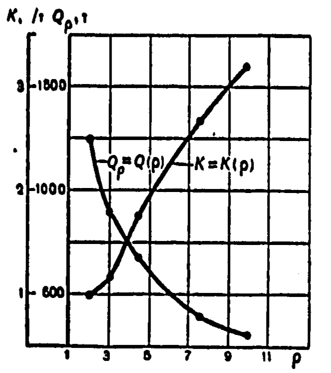

Figure 23. Effectiveness of steam treatments as a function of the output's water content.

extracted output, but on the absolute amount of water.

Table 15 and Figure 23 show the results of an investigation into the use of PTOS over a relatively long period of time (8 years). The factual data they contain indicate that steam treatments of wells with different degrees of flooding are highly effective when the temperature at the well bottom is raised to at least 120°C.

For instance, about 70,000 tons of oil (60 percent) was extracted from wells with an output water content of up to 2 tons/day and a steam-oil factor on the order of 1 ton/ton; 21,000 tons (18 percent) were extracted from wells with an output water content of up to 5 tons/day and a steam-oil factor of 1.65 tons/ton; 21,000 tons (18 percent) were extracted from wells with an output water content of up to 10 tons/day and a steam-oil factor of 2.7 tons/ton; 5,500 tons of oil (4 percent) were taken from wells with an output water content of 10 tons/ /day or more and a steam-oil factor of 3.3 tons/ton. As is obvious from the data that have been presented, as well as from Figure 23, the highest technical and economic indicators are

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obtained when the output's water content is no more than 2 tons/day. In this case, the additionally extracted oil exceeded 1,100 tons per treatment. As the water content increases to 5 tons/day, energy consumption increases somewhat, while the amount of additionally extracted oil per well treatment drops to 650 tons.

As the water content of the wells' output further increases to 10 tons/day and more, there is a corresponding increase in energy consumption and the amount of additionally extracted oil decreases to 350 tons per treatment; that is, in comparison with wells with a low water content, the effectiveness of the steam treatments is reduced by a factor of more than three.

In wells with a high output water content (5-10 tons/day and more), it is also possible to obtain profitable results, although the effectiveness of these treatments will be only one-third to one-fourth that of treatments of wells with low water contents. This is because of the increased energy consumption.

Consequently, when carrying out PTOS under analogous conditions it is first necessary to make technical and economic calculations of the process's effectiveness.

Effectiveness of Repeated PTOS's

For most wells there is a reduced flow rate after the first steam treatment, because of the small degree of envelopment of the bed by the heat carrier and little displacement of oil from the porous reservoir, the lowering of the temperature in the treated zone, the increase in the percentage of water in the extracted oil, and a number of other factors.

A project was formulated to conduct systematic, repeated treatments of a certain number of wells for the purpose of determining the final result of local steam treatment of the well-bottom zone of a bed and evaluating the final oil yield achieved by this method. More than 70 well treatments were performed over a long period of time in 30 wells, which were distributed in the following order as far as cycles of treatments are concerned: 16 wells -- 1 treatment; 16 -- 2; 14 -- 3; 12 -- 4; 6 -- 5; 5 -- 6; 4 -- 7.

In order to analyze the effectiveness of multiple steam treatmeants, the only wells investigated were those that were more or less -- from the viewpoint of the requirements for steam treatments -- under identical conditions. The results for the rest of the wells were not taken into consideration because of disparities in the conditions placed on the thermal treatment. For

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Table 16. Indicators of Multiple Steam Treatments in Wells With a Predominance of Microporous Reservoirs

(1)	(2)	(3)		(6)		(8)	(9)		(12)		(13)	(14)
		(4)	(5)	(7)	(5)		(10)	(11)	(10)	(11)		
1-я	16	21 000	21 000	1350	1 350	6300	13 200	820	13 200	820	1,6	25
2-я	16	21 000	42 000	1310	2 660	6400	7 120	445	20 320	1265	2,1	19
3-я	14	19 500	61 500	1360	4 020	6200	4 035	300	24 355	1565	2,5	13
4-я	12	18 000	79 500	1500	5 520	6600	2 800	235	27 155	1800	2,9	10,5
5-я	6	9 600	89 100	1600	7 120	3000	1 320	220	28 475	2020	3,2	9,0
6-я	5	8 500	97 600	1700	8 820	2500	825	165	29 300	2185	3,3	7,0
7-я	4	7 200	104 800	1800	10 620	2200	600	150	29 900	2335	3,5	6,5

Key:
1. Number of treatments
2. Number of well treatments
3. Amount of steam consumed for all wells, tons
4. For all wells
5. Cumulative
6. Specific steam consumption per well, tons
7. For one treatment
8. Water extracted from wells (steam condensate), tons
9. Additionally extracted oil, tons
10. Total
11. Per well treatment
12. Cumulative additionally extracted oil, tons
13. Steam-oil factor, tons/ton
14. Relative additional extraction of oil after well treatment, %

example, there were instances where the results of the second and third treatments were better than those of the first treatments. In connection with this, it was established that the main cause of this discrepancy was nonobservance of the PTOS regime; this was primarily due to not insuring that the temperature at the bottom of the well was high enough. Table 16 shows the indicators of effective PTOS's in wells with predominantly microporous reservoirs, in which the required PTOS regimes were observed. On the basis of the data that have been obtained, we also plotted graphs of the effectiveness of steam treatments as a function of the number of times the heat carrier was introduced into the bottom zones of wells and determined the steam-oil factors and total output (oil yield) of the treated zone (Figures 24, 25).

The indicators of oil yield according to laboratory data and the additional oil yield per well as the result of repeated

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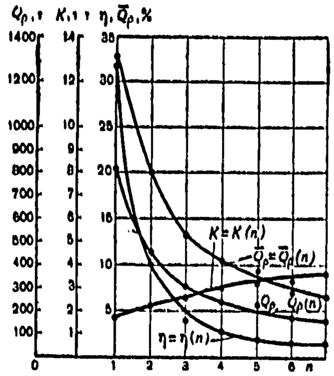

Figure 24. Additional extraction of oil Q_p, oil yield according to laboratory and field (η) data, relative additional oil extraction, functions of treatment cycles n, steam-oil factor K.

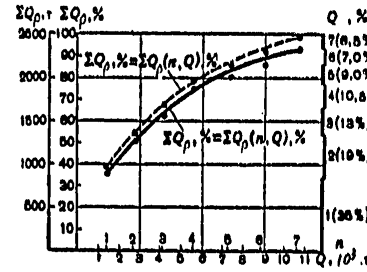

Figure 25. Dependence of total additional extraction of oil ΣQ_p on number of treatments n and steam consumption Q.

PTOS, as presented in Figure 24, are quite close together, since in both cases there is exploitation of certain sections of a bed. Because of the impossibility of exploiting a microporous reservoir by the usual method, in this case the final total oil yield can be taken as the oil yield factor. In connection with this there is a comparative relationship between the change in the oil yield factor obtained by the experimental industrial method and the change in the factor obtained by the purely experimental method.

As should be expected, there is an observable tendency toward a reduction in the process's effectiveness when repeated PTOS's are performed. Apropos of this, in the section "Effectiveness of Cyclic Steam Action on a Flooded Bed," in Chapter 4, we mentioned that the best results can be obtained for three or four cycles. In connection with this, at temperatures of 125, 150 and 200°C after the first cycle, from 35 to 53 percent, respectively, of the initial residual oil content was extracted. After the second treatment 10, 12.4 and 12.5 percent of the oil from the initial content was recovered at the above temperatures; after the third cycle, the corresponding figures were 4.2, 4.9 and 7.0 percent. On the whole, after the first four cyclic steam treatments, 54.0, 63.1 and 74.5 percent of the oil was extracted from a model bed. Field investigations to determine the effective criteria of multiple PTOS's were basically conducted at temperatures on the order of 120-125°C, with 51.4 percent of the remaining unextracted oil being removed after the first four cycles. This value is within the limits that are close to the oil yield obtained under laboratory conditions

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at temperatures of 125-130°C, which correspond to those used in the field experiments.

As the experiments showed, after a prolonged interval (more than 2 years) effective results were achieved for a number of wells after the eighth and ninth treatments, although the level of oil extraction was slightly lower (about 140-150 tons) than that obtained after the sixth and seventh treatments.

This is explained by the fact that oil continues to flow into the bottom zone of the well from other, untreated sections of the bed. Judging by the data obtained, however, oil filtration into the treated zone of a bed takes place slowly under conditions of low reservoir permeability and high viscosity of the oil, so that quite a long time is required for the porous reservoir in the treated zone to be completely filled with oil.

The greatest absolute quantity of extracted oil (77 percent) is also obtained after the first four treatment cycles. On the whole, and depending on the temperature to which the bed was heated, during the laboratory experiments the bed's final oil yield was 60.3, 68.5 and 77.0 percent. It should be mentioned here that during the laboratory experiments, the displaced oil was degasified and lacked the energy of the dissolved gas. Under field conditions this energy, which is one of the basic forces that moves high-viscosity oil along a bed, plays a rather important role in increasing a bed's final oil yield. This also explains the large effect achieved by repeated PTOS's in comparison with the laboratory experiments.

In connection with the absence of an influx of oil into the bed model, beginning with the fifth cycle the percentage of displaced oil drops abruptly. At temperatures above 150°C almost all of it is extracted after the first three cycles, and after the remaining cycles it is possible to increase the oil yield by little more than 2 percent. In the field experiments, however, up to the seventh cycle of steam treatments it was possible to increase the oil yield up to 5 percent after each succeeding cycle (beginning with the fifth one), which constituted 7-10 percent of all the additionally extracted oil after all the treatments.

Analyzing the effectiveness of multiple steam treatments and summing up the results of many years of experiments, it is possible to state that almost 80 percent (1,900 tons) of all the oil obtained is extracted after the first four treatments, while 35 percent (800 tons) of it is obtained after the first treatment. The average steam-oil factor does not exceed 2 tons/ton. After the next three cycles 20 percent (345 tons) of the oil is extracted, with a steam-oil factor of 3.3 tons/ton.

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Effectiveness of Frontal Displacement of the Oil in a Bed During Continuous Areal Injection of Steam

The problem of the industrial use of the continous injection of various heat carriers (hot water, steam, thermal waters, a steam and gas mixture, and others) into a bed for the purpose of frontal displacement of the oil in it has been discussed for a long time and, in comparison with PTOS, has a considerably longer history. Many aspects of this question have been subjected to a more profound theoretical analysis and certain laboratory and test-bench investigations have been conducted in order to determine the criteria necessary to insure the implementation of the process with high technical and economic indicators [17,25,26,37,59]. At the same time, field experiments and the industrial introduction of this process, which would be of great practical value, are still lagging behind significantly. One of the main reasons for the slow introduction of continuous steam injection into a bed is the difficulty of controlling and regulating the process, particularly under the complex geological conditions presented by highly heterogeneous reservoirs. Although the theoretical principles of the continuous injection of steam for the purpose of frontal displacement of oil were advanced by Soviet authors, this method was first used extensively in practice in the United States, from 1958 to 1961 in the state of California. By 1965 in California, alone, it was being used in 17 areas, while by 1966 and 1970 it was being used on 40 and 50 projects, respectively [59].

As a rule, oil-extracting companies use continuous areal injection in fields with relatively favorable geological conditions, where the oil deposits occur at shallow depths (up to 700-800 m). As far as oil deposits represented by reservoirs with a high degree of heterogeneity are concerned, the continuous injection method is not yet used on them, although they are of interest and research is being done in this field in the United States.

Below we present the basic generalized bed parameters and other criteria used in implementing continuous steam injection in the United States in deposits with favorable geological conditions.

Depth of occurrence of oil-bearing bed, m . .	50-800
Type of reservoir	Sands and sandstones with alternating thin interlayers of clay
Bed thickness, m.	15-75

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Effective thickness, m.	8-35
Reservoir permeability, D	0.5-5
Oil saturation, %	60-75
Oil viscosity, cp.	200-1,500
Oil density, g/cm^3.	0.950-0.970
Area of experimental sections, ha	2-45
Well placement network.	5-7 points
Distance from injection to operating well, m.	20-50, infrequently up to 90
Area of a single element, ha.	From 0.1-0.25 to 1-4
Number of observation wells on a project. . .	4-15
Number of simultaneously operating elements in an area.	Up to 10
Average rate of steam injection, depending on the distance between the wells, tons/day. .	50-170
Total amount of heat carrier supplied to a single element, depending on the area and volume of the oil-saturated rock being treated, tons x 1,000	50-200
Duration of process, yrs.	2-5
Additionally extracted oil, tons x 1,000. . .	15-60
Steam-oil factor, tons/ton.	0.3-2.5
Coefficient of coverage by heat carrier, according to data gathered from specially drilled wells, %:	
By thickness.	40-50
By area	60-85
Increase in oil yield factor by section (element)	40-77

The process of continuous steam injection into a bed is complicated by breaching of the well-bottom zone of operating wells and the loss of sand, the formation of stable oil emulsions, the operation of "overheated" wells, and an inadequate supply of high-quality water.

In the United States it is thought that from the viewpoint of economics, continuous areal injection of steam is related to high operating costs because of the duration of the process; this applies primarily to energy consumption (the cost of fuel and water).

In Soviet practice the most successful results for continuous steam injection into a bed have been obtained by the Sakhalinneft' association, where, under relatively favorable geological conditions in the Okhinskoye field, in 1968 areal steam treatments were carried out [30]. The object chosen for the

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continuous injection of steam was the oil pool in Bed 4, Block 9, which lies in the central part of the fold at a depth of 90-150 m and has an average thickness of 60 m. The bed's parameters are as follows: porosity -- 28 percent; permeability -- 1 d; degree of oil saturation -- 80 percent; oil density under surface conditions -- 0.93 g/cm^3; viscosity -- 165 cp; tar content -- 45 percent. The formation pressure at the beginning of the work was 1-3 kg/cm^2 at a bed temperature of 4-6°C.

Before the use of PTV on the bed, its oil yield factor had been 0.14 for more than 40 years. In this area, 52 wells grouped into 9 separate development elements were drilled. The area of each element varied from 0.34 to 0.87 ha.

The sizes of the separate development elements were deliberately varied, for the purpose of determining the effectiveness of the process for different distances between wells. Both existing operating wells and ones that were newly drilled for this purpose were used as steam injection wells.

Each injection well served 7-10 operating wells that were, on the average, 50-60 m apart. The process was implemented by the average daily injection into each injection well of 50-60 tons of steam at an injection pressure of 8-24 kg/cm^2 and a well-mouth temperature of 170-280°C.

Over a 2-year period, the total amount of steam injected into the separate elements of the area was 25,000-40,000 tons. The amount of additional oil extracted was 61,000 tons. The steam-oil factor fluctuated from 1.7 to 12.5 tons/ton and averaged 3.6 tons/ton. The section's oil yield factor rose from 0.13 to 0.238, and for separate elements was as high as 0.4-0.5.

Along with continuous injection of steam into an element of the section being developed, steam treatments of the operating wells were also carried out. In addition to increasing the oil flow rates, this contributed to the creation of a hydrodynamic link between the steam injection and operating wells. Instances where the steam broke through into the operating wells were observed when protracted steam repression was practiced. In order to combat the breakthrough of steam into the operating wells, small volumes of cold water were injected.

The basic complications that arise during areal steam injection are:
1) breakthrough of the steam into operating wells, which leads to a reduction in the oil recovery rate in these wells;
2) intensive plug formation;
3) jamming of the pistons of borehole pumps at high temperatures (100°C or higher).

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In order to combat steam breakthroughs, available methods were used, including: reducing the steam injection rate, reducing the amount of liquid removed, injecting cold water into the reacting well, and temporary cessation of steam injection.

As far as measures for sand removal were concerned, no success was achieved in trying to find ways to strengthen the bottom zone of the wells, although carbamide tars were used to combat sand formation.

The problem of operating borehole pumps under high-temperature conditions also remains unsolved.

Work was begun in 1969 on the continuous injection of steam in an experimental section of the Khorasany field, which belongs to Azneft' [State Association of the Azerbaydzhan Petroleum Industry], where the bed's depth of occurrence is 500-700 m. A reaction was observed in operating wells located at a distance of 80-90 m from the injection well 3-4 months after the beginning of the process. The flow rates increased to 3-4 tons/day. Here, as in the Okhinskoye deposit, one of the main obstacles to normal implementation of the process was intensive plug formation in the operating wells.

Work is being done to introduce continuous steam injection in other oil regions, including: the Kazakh SSR (Kenkiyak and Uzen' deposits), Sakhalin Island (the Katangli deposit), the Komi ASSR (the Yarega deposit), and the Bashkir ASSR (the Arlan deposit).

The projects for continuous steam injection into a bed that are being implemented and planned in these regions primarily involved areas of regular lithological uniformity of the bed and the granular reservoir. Under these conditions, the technical and technological problems that arise can undoubtedly be overcome much more easily than in the case where the oil deposits are confined to beds with increased nonuniformity. Therefore, from the very beginning of the use of steam treatments of wells represented by micro- and macroporous reservoirs, the investigation of the effectiveness of the known production processes was accompanied by another goal -- the development and implementation, under complicated geological conditions, of a thermohydrodynamic process that would insure a high degree of bed coverage and a high final oil yield under the indicated conditions.

Two processes for continuous steam injection into a bed were used in specially prepared areas during the period of experimental industrial research. Below we present the results of the investigations of these processes' effectiveness.

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Selection of Experimental Sections for Areal Injection of Steam Into the Bed

The selection of the experimental sections for continuous steam injection was based on the field geological characteristics of the Zybza deposit, the reservoir's facies variability, and the linkage between the provisionally selected oil-bearing beds and their degree of exploitation. For these reasons, Special Sections 1 and 2 were selected in the northern and southern parts of the field. Their characteristics are presented below.

During the selection process it was assumed that the oil from the highly permeable reservoir was almost exhausted and that the basic (about 86-90 percent) unextracted reserves were located in the porous part of the bed. Precisely stated, the problem was to find the appropriate technological method of exerting steam action on the bed in order to displace the oil from the porous part of it.

Experimental Section 1 (Figure 26) is located in the northwestern part of the deposit and is being worked by 15 wells drilled into horizons 8 and 9, which lie in Sarmatian deposits at a depth of 750 m. The section is represented by two types of reservoirs: microporous, with permeability of up to 250 md, and macroporous, which is of subordinate value. The wells were drilled in a triangular network, with a distance between wells of 100 m. The area of each element averages 2.5 ha, while the area of the entire experimental section is 21.5 ha. The reservoir's rock volume is approximately 13 million m^3.

The formation pressure at the time of steam injection (1969-1970) fluctuated from 3.5 to 15 kg/cm^2.

During this period of deposit development, many wells in the section went into operation with flow rates of 30-70 tons/day, because of the presence of the highly permeable macroporous reservoir, after which -- as is characteristic for a reservoir of this type -- there was a sharp decline in the flow rates. During the period of most intensive deposit development (1949-1951), the average daily amount of oil extracted from the wells in the section reached 500 tons. After 5 years, however, this figure dropped to 50 tons, and by the time steam treatments began to be used (1965) it had reached 2-3 tons; that is, the extractive possibilities of the section had been almost completely exhausted. Before the beginning of areal steam injection (1970) the well flow rates were 0.1-0.5 tons/day, except for Well 383 where it was 3.5 tons/day. The water content of the output varied from 5 to 90 percent. The section's total annual oil yield was 820 tons.

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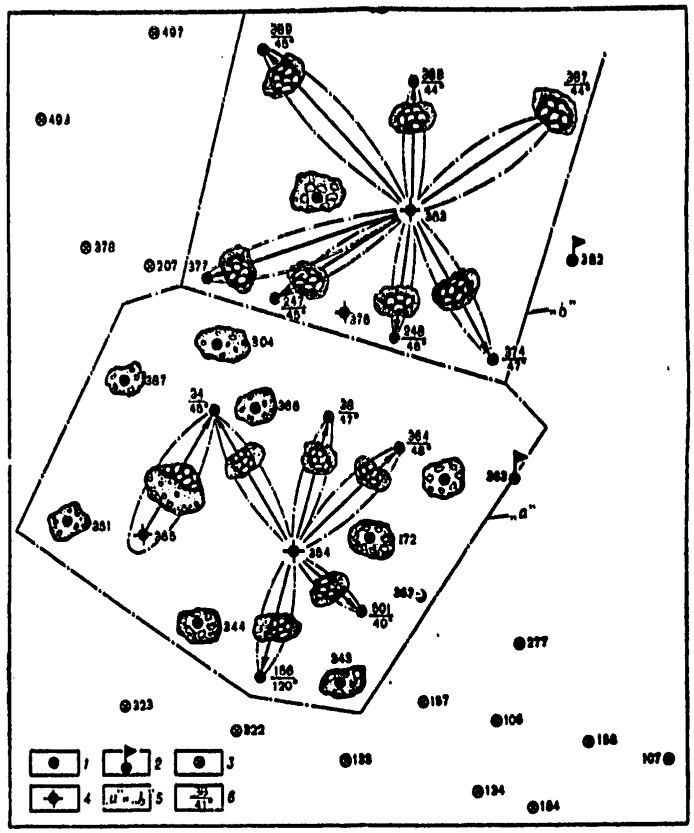

Figure 26. Diagram of movement of thermal flows during areal steam action on the bed in Section 1. Wells: 1. operating-observing; 2. observing; 3. abandoned; 4. steam injection; 5. conventional deposit development elements; 6. well number in the numerator, well-mouth temperature in the denominator.

Experimental Section 2 (Figure 27) was located in the elevated southern part of the Zybza field, where a dissolved gas regime with the formation of a gas cap developed at the beginning of the exploitation period. Subsequently, many wells in this zone were abandoned because of the presence of the gas. By the time of the experimental project to displace the oil by a heat carrier, there was almost no gas in the wells and the level of the liquid column had dropped sharply and did not exceed 10-15 m.

In this section, the depth of occurrence of the oil-bearing deposits varies from 440 to 735 m. Here the profile is also

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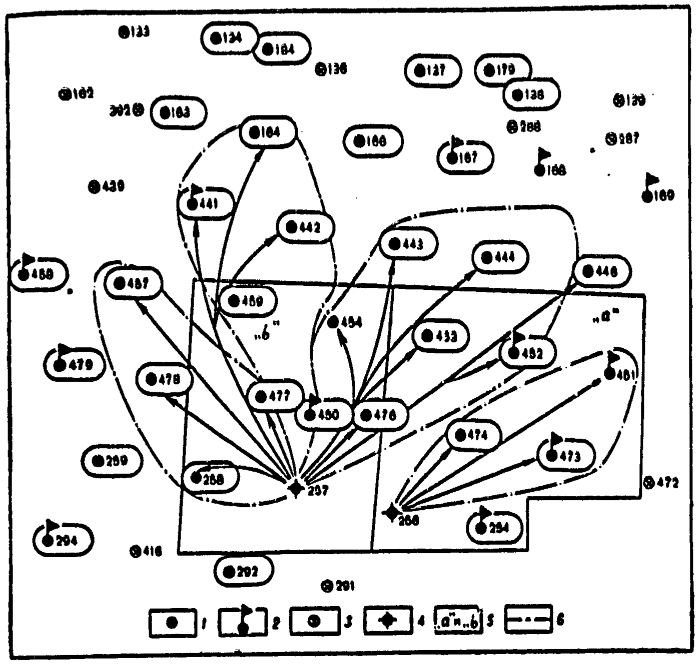

Figure 27. Diagram of well location and thermal flow movement in Section 2: 1-5. see Figure 26; 6. outlines of thermal flows.

represented by micro- and macroporous reservoirs. The effective thickness of the productive beds reaches 130 m. Because of its gas content, at the beginning of its development this section was almost completely shut down, and then as the gas was depleted several wells were put into operation with flow rates of up to 10 tons/day.

By the time areal steam injection was begun, the wells were being operated with a flow rate of 0.1-2.5 tons/day. The section's total annual oil output was 1,960 tons. The section is being developed by 20 wells, with an output water content that does not exceed 5 percent.

Equipment and Technology for the Areal Injection of Steam Into a Bed (Figure 28)

In view of the fact that the operating equipment in the field was not adaptable to the use of thermal effects, there was a preliminary investigation of all the wells to determine the tightness and integrity of the casing string, while additional capital work was done on the steam injection wells in order to

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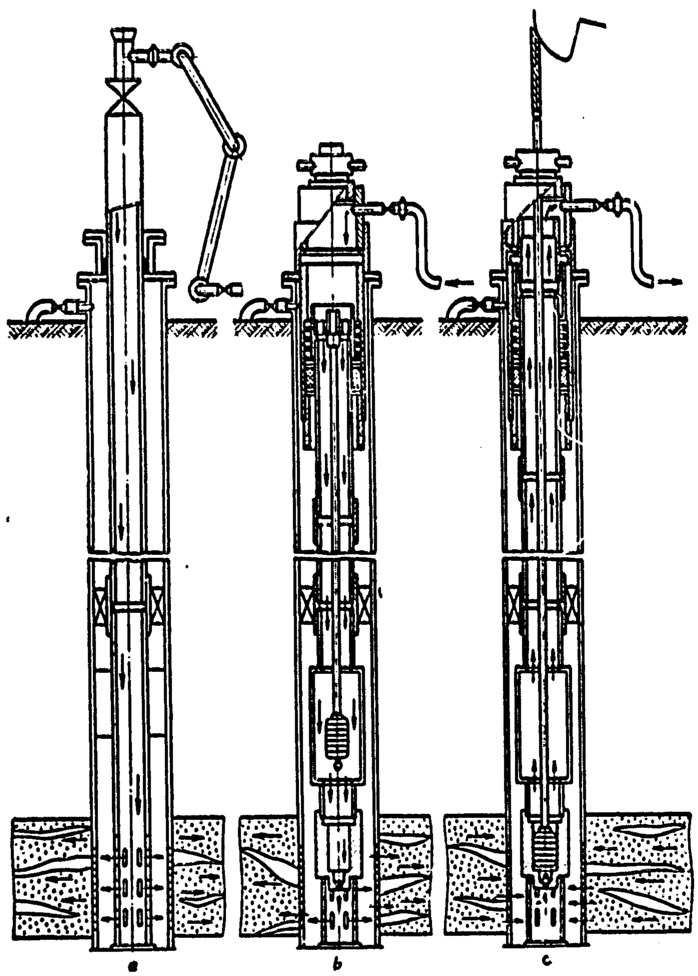

Figure 28. Improved verions of equipment and well-mouth framework for steam injection wells: a. collar device, insuring mutual mobility of casing and pumping-compressing strings; b, c. telescopic devices, insuring elongation of pumping and compressing pipes, respectively, without raising the pump and in the process of removing liquid.

create reliable conditions during the injection of steam into the bed. In Section 1, for instance, where our calculations led us to expect protracted injection of the heat carrier, steam injection wells 354 and 365 were additionally equipped

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with 102-mm casing pipe and cemented up to the mouth, thereby creating a reliable string that insured the normal conduct of the process. In contrast to Section 1, the injection wells in Section 2 were equipped with 63-mm pumping-compressing pipes and a packer.

Steam injection was carried out from a stationary DKVR-10/39 boiler equipped with a Soviet PSP unit and a Takuma (Japanese) steam generating unit. In Section 1, steam was injected through four wells (354, 356, 376, 383), while only two (256, 257) were used in Section 2. The process was begun in Section 2 in February 1970 and in Section 1 in May of that year.

The average daily rate of steam injection into an areal element through the wells in Section 1 was, depending on receptivity, 70-90 tons, while in Section 2 it was 100-150 tons per well. The steam temperature at the well mouth was 215-220°C, while the pressure was 25-35 kg/cm^2.

In order to observe the movement of the heat carrier's front and regulate the process, monitoring was carried out in both sections, both directly in the operating wells and in specially designated observation wells in which the following parameters were recorded on a regular basis:
1) operating wells -- change in liquid flow rates and temperature at the well mouth, chlorine ion content in the formation water;
2) observation wells -- change in the static level in the wells and the bed temperature in the range of the filter.

Let us examine the results of the process separately for the two sections.

Section 1

This section was provisionally divided into development elements "a" and "b," as shown in Figure 26. Steam injection into element "a" was begun simultaneously through wells 354 and 356, and into element "b" from the north, through wells 376 and 383. It was assumed that the oil would be displaced through the adjacent row of operating wells positioned linearly (in a row) between injection wells 354 and 356 in the most favorable (from the geological viewpoint) zone. This undoubtedly did not eliminate the possibility of a reaction in other wells, because of the presence of two types of reservoirs in this section.

The most stable steam injection was into element "a" through wells 354 and 356, into which 52,000 and 49,000 tons of steam were fed, respectively, over a period of 650 days.

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In 350 days, 30,000 tons of steam were fed into well 383 (element "b"). The process was halted because of the impossibility of monitoring and regulating the movement of the heat carrier.

On the whole, the areal injection experiment lasted almost 2 years (from 1970 to 1972), with continuous areal injection being stopped after completion of the planned program.

In order to create a hydrodynamic link between the rows of operating wells, steam treatments were carried out in the section. During the period indicated above, treatments were carried out in 10 wells (257, 343, 156, 207, 38, 367, 34, 344, 364, 377). About 11,000 tons of steam were used for this purpose.

Thus, throughout the duration of the entire process, 142,000 tons of steam were injected into the wells of Section 1 and 18,500 tons of oil were extracted.

Beginning, basically, in the second half of 1976, individual wells began to interact with the injection wells. The most effective proved to be those operating in development element "a". For instance, the average monthly oil yield was 15 tons for well 156, which was located up the dip of the bed. After the steam treatment and further reaction with well 354, this well's flow rate tripled and reached 50-60 tons per month, on the average, for separate periods.

The increase in the oil flow rate was affected by the steam treatment (850 tons of steam were fed into the well) as well as the injection of steam into well 354, from the direction of which there was frontal displacement of the oil. As has already been mentioned, as the steam was injected into the bed the advance of the heat carrier was monitored, both by the change in the chlorine ion content in the extracted formation water and by the change in the temperature at the well's bottom and mouth. Seven months after the beginning of steam injection into well 354, in reacting well 156 there began to be a decrease in the chlorine concentration that by the time of considerable flooding of the output had dropped from 6 to 0.85 g/liter.

There was intensive penetration of the steam condensate through the highly permeable macroporous reservoir, which led to an increase in the amount of water extracted. Although 1.5 tons/day of water were extracted from the well at the beginning of the process, after 7 months the water flow rate had risen to 12 tons/day, while the temperature at the well mouth had increased to 40°C as opposed to the average annual temperature of 18-20°C.

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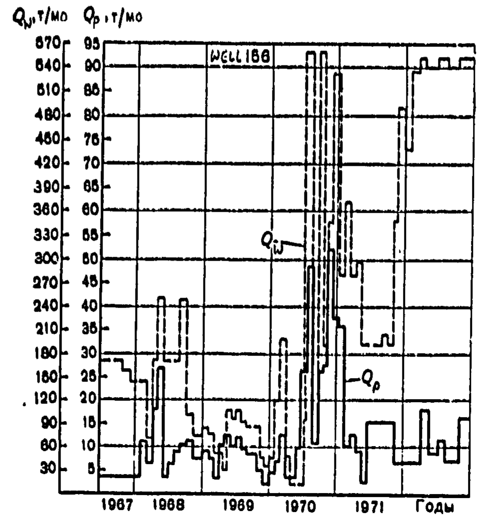

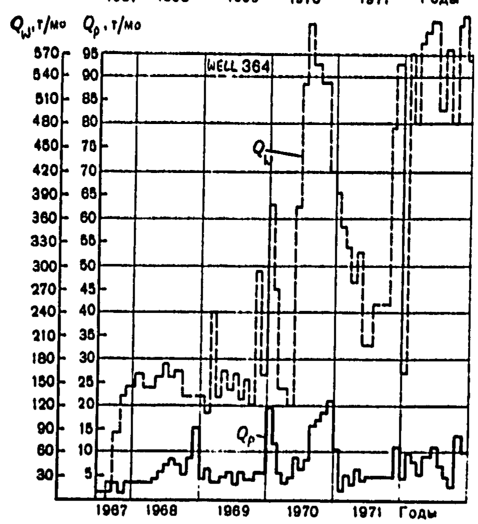

Figure 29. Change in flow rates of wells 156 and 364 during continuous steam injection in Section 1.

By this time the average daily oil flow rate had reached 1.5-2 tons instead of the 0.5 tons it averaged before the reaction.

Well 364, which is located 100 m down the dip of the bed from injection well 354, also began to react to the injection of steam. Six months before the beginning of the process the oil and water flow rates were 0.5 and 3.5 tons/day, respectively,

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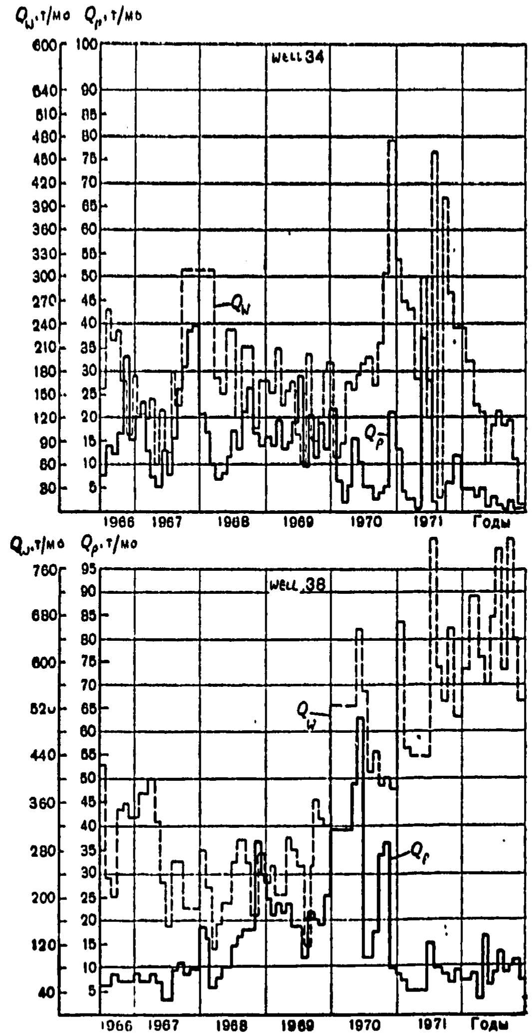

Figure 30. Change in flow rates of wells 34 and 38 during continuous steam injection in Section 1.

while 2 months after the beginning of areal injection of steam (June 1970), the well's productivity increased to 1.5 tons/day, while the water yield was 12 tons/day. By the third month there began to be an intensive drop in the chlorine ion concentration and a progressive increase in the amount of water in the output that reached 20 tons/day. The temperature at the well mouth rose to 48°C.

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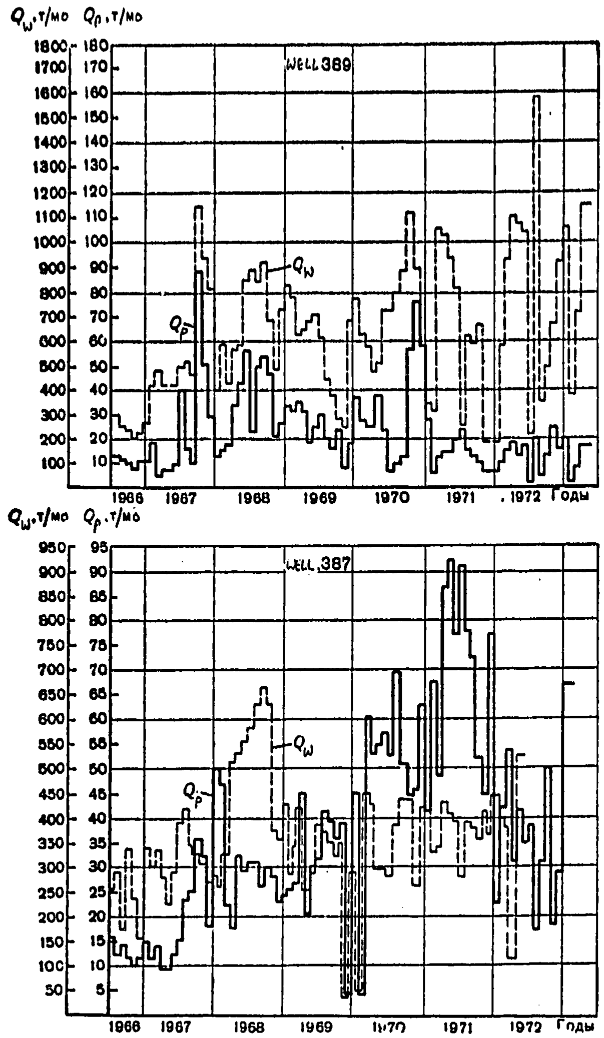

Figure 31. Change in flow rates of wells 387 and 389 during continuous steam injection in Section 1.

Wells 34 and 38, which are located in development element "a," are within the sphere of influence of wells 354 and 356. Despite the seemingly identical characteristics of the reservoir, according to logging data the wells' behavior during the period of continuous steam injection did not turn out to be the same. For instance, well 38's liquid flow rate was 10 tons/day (of

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which 1 ton was oil) before the steam treatment, but just 15 days after the beginning of the process the water and oil flow rates had increased to 25 and 3 tons/day, respectively. After 6 months the comparable figures were 35 and 4 tons/day. The well-mouth temperature had risen to 47°C.

The situation was somewhat different with well 34, which for a long time had operated with oil and water flow rates of 0.5 and 6 tons/day, respectively. After 6 months, however, there was a sharp increase in the liquid flow rate, to 10 tons/day (of which 1 ton was oil), and after yet another month it rose to 15 tons/day (of which 1.5 tons were oil). The well-mouth temperature reached 45°C.

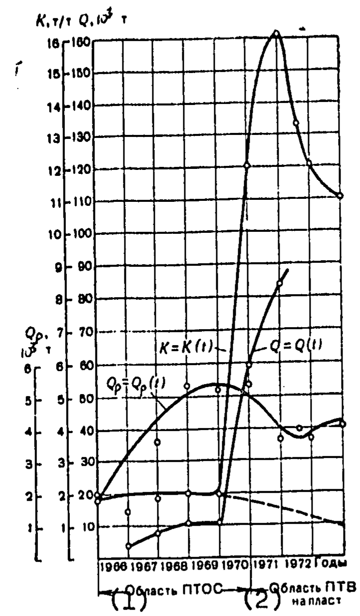

Figure 32. Results of effectiveness of PTOS and PTV in Section 1.
Key: 1. PTOS area
2. Area of PTV on bed

Let us discuss the operating wells located within the sphere of influence of well 383: 387, 388 and 389, which are in a somewhat elevated zone relative to the injection well, and 248 and 377, which are situated down the dip of the bed. The best results were obtained with well 387.

Here, in connection with the predominance of microporous reservoirs and because of the slow advance of the steam condensate through the bed and the displacement of the oil from the microporous into the macroporous reservoirs, there was a gradual increase in the wells' flow rates. For instance, 3-4 months after the beginning of the process, the daily flow rate of well 387 had increased from 0.1-0.2 to 3-3.5 tons, in connection with which no substantial breakthrough of steam condensate into the well, which was located up the strike from the steam injection well (as has already been mentioned), was observed. At the same time, a steam condensate breakthrough was observed in well 389, which was located on the same hypsometric mark as well 387.

Wells 248 and 377 behaved somewhat differently. Since they were located somewhat down the bed's dip relative to operating

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Table 17. Basic Indicators of Oil and Liquid Extraction and Heat Carrier Supply for Section 1

(1)	(2) Количество пара для ПТОС, тыс. т		(5) Добыча нефти по участку, тыс. т		(6) Площадное нагнетание пара, тыс. т		(7) Добыча нефти по участку за счет непрерывного нагнетания пара, тыс. т		(8)	(9) Паронефтяной фактор	
Годы	(3) за год	(4) по нарастанию	(3) за год	(4) по нарастанию	(3) за год	(4) по нарастанию	(3) за год	(4) по нарастанию	Добыча жидкости, тыс. т	(10) за счет ПТОС, т/т	(11) за счет площадного нагнетания, т/т
1966	3,7	3,7	2,6	2,6	—	—	—	—	50,6	1,4	—
1967	7,2	10,9	3,0	5,6	—	—	—	—	61,4	1,9	—
1968	10,5	21,2	5,2	10,8	—	—	—	—	63,4	1,95	—
1969	10,0	31,2	5,2	16,0	—	—	—	—	49,8	1,9	—
1970	57,8	89,2	5,3	21,3	57,8	57,8	5,3	5,3	64,7	—	11
1971	83,8	172,8	3,2	24,5	83,8	141,6	3,2	8,5	62,7	—	16
1972	—	172,8	4,5	28,0	—	141,6	4,5	12,0	69,0	—	12
1973	—	172,8	5,5	34,5	—	141,6	5,5	18,5	70,0	—	7

Key:
1. Year
2. Amount of steam for PTOS, tons x 1,000
3. For the year
4. Cumulative
5. Oil extracted from section, tons x 1,000
6. Areal injection of steam, tons x 1,000
7. Oil extracted from section because of continuous steam injection, tons x 1,000
8. Liquid extraction, tons x 1,000
9. Steam-oil factor:
10. Because of PTOS, tons/ton
11. Because of areal injection, tons/ton

wells 387, 388 and 389, they reacted quickly to the injection of steam into wells 383 and 376. For instance, after 2 months the oil flow rate from well 248 rose from 0.5 to 2.5 tons/day and the water flow rate increased from 3 to 13 tons/day, while after 6 months the comparable figures were 3.5 and 15 tons/day. An analogous pattern was observed for well 377, which also reacted quickly to the injection of steam.

Thus, as the result of the protracted injection of steam, almost all the operating wells in the section reacted to some degree or another and, on the whole (as is obvious from Figure 32), there was an increase in the operating wells' oil yield because of the continuous injection of steam. There was an investigation of the effectiveness of this process in comparison with periodic steam treatments of wells that were carried out systematically in the same section for 4 years before the beginning of areal injection.

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As a result of the steam treatments of wells that were performed here from 1966 to 1969, 16,000 tons of oil were extracted with an average steam-oil factor of 1.8 tons/ton. On the basis of calculated data, it was assumed that 2,000 tons would have been extracted during this period without the treatments. Figure 32 and Table 17 contain comparative results for the two technological processes implemented in Section 1 under the same geological conditions. The data presented and the results of the investigation of the factual material show that from the beginning of the experimental industrial work on areal injection of steam (see the PTV area in Figure 32), the effectiveness of the process began to drop in comparison with PTOS (see the PTOS area). For instance, the steam-oil factor for oil extracted after areal injection reached a maximum of 16 tons/ton and had a minimum of 7 tons/ton; that is, the energy consumed to displace 1 ton of oil was greater than that used for steam treatments by a factor of 6-7.

Section 2

This section is located in the elevated area of the bed. Here the basic group of wells was abandoned in the early period of the deposit's development because of the amount of gas in the oil. Considering the fact that there are large residual reserves of oil in microporous reservoirs, it was suggested that it be displaced downward, making simultaneous use of the force of gravity. For this reason, the steam injection wells were situated in the elevated part of the area, while the operating wells were located down the dip of the bed. The developers did not forget to create a water-vapor fringe in the elevated degasified zone of the bed that was capable of displacing ultraviscous degasified oil from the porous part of the bed into the ducts of the macroporous reservoir, after which it was displaced by the movement of the thermal column, which was impelled forward by the addition of a calculated amount of cold water through the steam injection wells. In connection with this, it was hypothesized that there would be a recuperative effect along with the increase in the process's efficiency.

Wells 256, 257 and 258, which were located in the elevated zone of the bed, were used for steam injection. In order to monitor the heat carrier's movement, the wells prepared for both observational and operational use were 292, 453, 454, 477, and 478, which were located down the dip of the bed at a distance of at least 100 m from the injection wells. In these wells, low liquid levels and insignificant formation pressures (1-3 kg/cm^2) were registered.

The area of the entire section that was monitored was about 20 ha, with the volume of the hypothetically oil-saturated rock

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being calculated at 15 million m^3. The area of the provisionally distinguished elements was 2.5 ha.

The layout of Section 2 is shown in Figure 27. Here the productive deposits lie at depths of 500-550 m. The oil density, as measured at moment of steam injection into the bed, ranged from 0.985 to 0.990; its viscosity at 30°C exceeded 2,000 cp.

Steam began to be injected into wells 256, 257 and 258. Subsequently, well 256 was abandoned for technical reasons. The steam repression in Section 2 continued for 2 years. On the average, 120-170 tons of steam at a pressure of 25-30 kg/cm^2 and a well-mouth temperature of 220-225°C were injected into the wells every day.

During the process of steam injection into well 256 (element "a"), a good hydrodynamic link was established with well 474, located down the dip of the bed at a distance of 100 m from the injection well. Five days after the beginning of steam injection, an increase in the liquid level in well 474 w s registered, after which it was put into operation. Its flow rate at the initial moment of operation was 1.5-2 tons/day of liquid. The well was observed carefully. A systematic increase in the liquid flow rate up to 10-15 tons/day was established, and after 60 days the extracted output rose to 30 tons/day. At the same time, there was an increase in the well-mouth temperature of the liquid, to 39°C (as opposed to the average annual temperature of 18°C). The chlorine ion content dropped to 1 g/liter. By this time the well's oil flow rate was more than 3 tons/day. In order to regulate and improve the efficiency of the process, operation of the steam injection well was halted periodically. As the steam injection period increased in duration, a sharp increase in the pressure at the well mouth was observed. During the cessation of steam injection into well 256 (periods of up to 10-15 days), a reduction in the liquid flow rate from well 474, along with a simultaneous increase in the oil yield, was observed.

As a result of the periodic stops and starts of the steam injection well's operation, after about 85-90 days there were clearcut qualitative changes in the extracted output ratio for the reacting well. For instance, the well's liquid flow rate dropped to 15 tons/day, while the oil flow rate reached 12-14 tons/day.

These experiments in periodic areal injection, which were carried out in reservoirs with increased heterogeneity [12], were used in the course of the work on continuous steam injection and yielded positive results. After this, steam injection

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through well 256 was halted and the heat carrier began to be supplied through well 257. Nevertheless, oil continued to be obtained from well 474 for a long time (more than 2 years). By the end of this period, the flow rate dropped to 2-3 tons/day. After the changeover to steam injection through well 257, which was located 170 m away from well 474, no effect on the latter was registered throughout the duration of the entire process. Thus, only well 256 influenced the effective operation of well 474.

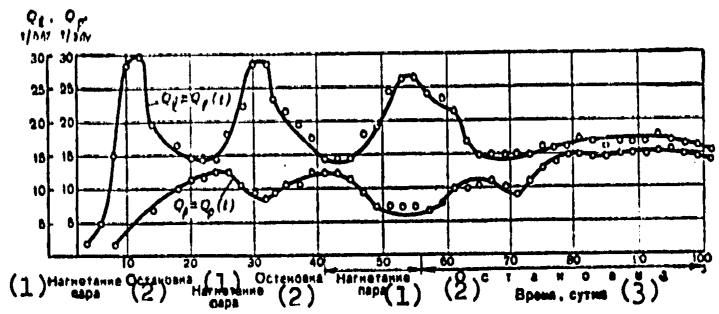

Figure 33. Change in flow rate of operating well 474 as a function of the cycles of heat carrier injection into well 256.

Key:
1. Steam injection
2. Stoppage
3. Time, days

Figure 33 shows the dynamics of well 474's operation throughout the entire period. It has been calculated that 1,950 tons of oil were extracted from the well -- previously considered to be "dry" and abandoned -- during its effective period. If we relate all the steam fed into the bed through well 256 (about 6,700 tons) to the oil extracted from well 474, the steam-oil factor will be 3.3 tons/ton, which is an extremely satisfactory technical and economic indicator. Later this indicator dropped sharply.

In connection with this, the steam effect began to be exerted through well 257, which was also located in the elevated zone of the bed. Throughout the entire period, injection was performed through this well under an almost constant steam injection regime: 160-170 tons/day at a temperature of 220-225°C and a well-mouth pressure of 35-40 kg/cm^2. In order to regulate and control the movement of the heat front, temperature, hydrodynamic and geochemical observations were made in the surrounding wells. After 6,750 and 7,800 tons of steam were fed into wells 256 and 257, respectively (6 months after the beginning of the experimental work), the temperature in well 476

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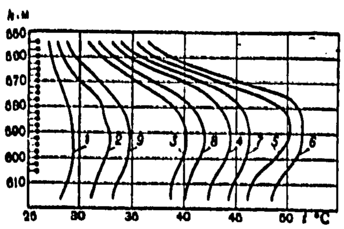

Figure 34. Change in temperature in well 476 during displacement of the thermal fringe by cold water.

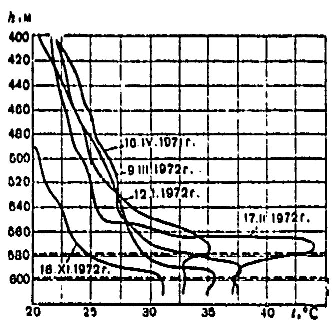

Figure 35. Temperature changes at the bottom of well 477.

(situated 100 m from the injection well) had risen to 48°C, that in well 454 (170 m away) had increased to 40°C, and in well 564 (200 m away) it had reached 39°C. Subsequent measurements registered an increase in temperature for well 477 (41°C) as well as the ones mentioned above.

As a rule, an increase in temperature was registered for wells located down the dip of the bed. No changes in temperatures were recorded at the bottoms of wells situated up the dip of the bed. As steam was injected, the thermal front advanced, with an unevenly shaped outline, down the dip of the bed through the most permeable reservoir (the macroporous one). Figures 34 and 35 show the temperature profiles measured in wells 476 and 477 during the process. In connection with the presence in this zone of a highly permeable macroporous reservoir, the heat carrier broke through from the injection well to significant distances without displacing oil from the microporous reservoir.

For the reacting wells listed above, a simultaneous increase in the liquid levels was observed. For instance, a column of liquid up to 30-35 m tall appeared in "dry" well 476, while in well 258 the column was up to 20 m tall. In other wells located even farther from the steam injection well (up to 300 m), penetration of the steam condensate was also observed, which is indicated by the change in the geochemical composition of the water in wells 441, 442, 443, 444, 446, and 457. In the course of a year, the chlorine ion content in the extracted water decreased from 6-7 to 2 and 3 g/liter; that is, in these wells there was freshening of the extracted water and an increase in its flow rate (Figure 36).

On the whole and in the course of but a single year, over an area of almost 20 ha (instead of the expected 2.5 ha) there was

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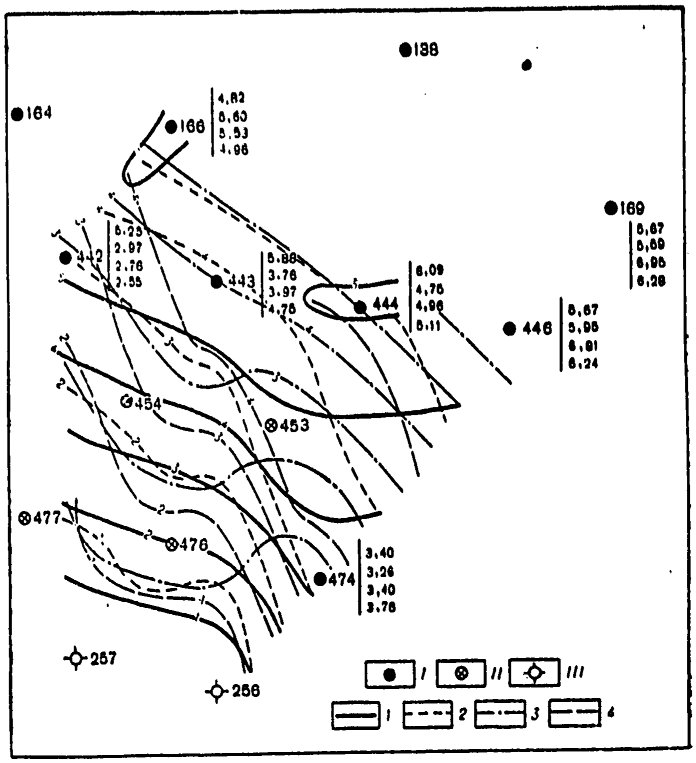

Figure 36. Change in chlorine ion content in formation water for wells in Section 2. Wells: I. operational; II. abandoned; III. injection. Dates: 1. 25 May; 2. 29 June; 3. 7 July; 4. 24 July.

observed dissemination of the steam condensate, which in this case was an undesirable process.

In connection with the cooling of the steam condensate, for all practical purposes there was an intrusion of water into the operating wells at a somewhat higher temperature than that of the formation water; this did not have any effect on the oil yield. In the final stage, this process was close to the one of maintaining the formation pressure by injecting water, which was performed during the early stage of development of this deposit and which proved to be ineffective because of the intensive breakthrough of water along the highly permeable ducts of the macroporous reservoir. On the whole, for the section under discussion there was not only no increase in the wells' oil flow rate but, on the contrary, it was observed to decrease.

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Table 18. Basic Indicators of Oil and Liquid Extraction and Heat Carrier Supply for Section 2

(1) Годы	(2) Количество пара для ПТОС, тыс. т		(5) Добыча нефти по участку, тыс. т		(6) Площадное нагнетание пара, тыс. т		(7) Добыча нефти по участку за счет непрерывного нагнетания пара, тыс. т		(8) Добыча жидкости, тыс. т	(9) Паронефтяной фактор, т/т	
	(3) за год	(4) по нарастанию	(3) за год	(4) по нарастанию	(3) за год	(4) по нарастанию	(3) за год	(4) по нарастанию		(10) за счет ПТОС	(11) за счет площадного нагнетания
1966	0,8	0,8	0,3	0,3	—	—	—	—	0,8	2,6	—
1967	3,9	4,7	5,4	5,7	—	—	—	—	16,4	0,75	—
1968	2,7	7,4	4,6	10,3	—	—	—	—	23,0	0,72	—
1969	2,9	10,3	4,8	15,1	—	—	—	—	23,8	0,67	—
1970	—	10,3	1,7	16,8	49,9	49,9	1,7	1,7	24,4	—	29
1971	—	10,3	2,4	19,2	132,7	182,6	2,4	4,1	24,3	—	45
1972	—	10,3	2,5	21,7	—	182,6	2,5	6,6	24,5	—	28
1973	—	—	2,4	24,1	—	182,6	2,5	9,1	24,6	—	20

Key:
1. Year
2. Amount of steam for PTOS, tons x 1,000
3. For the year
4. Cumulative
5. Oil extracted from section, tons x 1,000
6. Areal injection of steam, tons x 1,000
7. Oil extracted from section because of continuous steam injection, tons x 1,000
8. Liquid extraction, tons x 1,000
9. Steam-oil factor:
10. Because of PTOS, tons/ton
11. Because of areal injection, tons/ton

There was an investigation of the effectiveness of this process (as was done for the first section) in comparison with the effectiveness of the steam treatment process that was implemented here before the continuous injection of steam began.

Table 18 and Figure 37 show the basic technological indicators before and after PTOS, including the continuous steam injection process. From the data presented it is obvious that during the PTOS period, an average of about 5,000 tons of oil were extracted every year for an almost constant yearly liquid output of 23,000-24,000 tons. During the 3 years of steam treatments, 10,000 tons of steam were expended and an additional 15,000 tons of oil were obtained; that is, the steam-oil factor in this section during PTOS proved to be lower than unity (about 0.7).

Since 1970, when continuous steam injection began, oil extraction from this zone has dropped because of the heat carrier's

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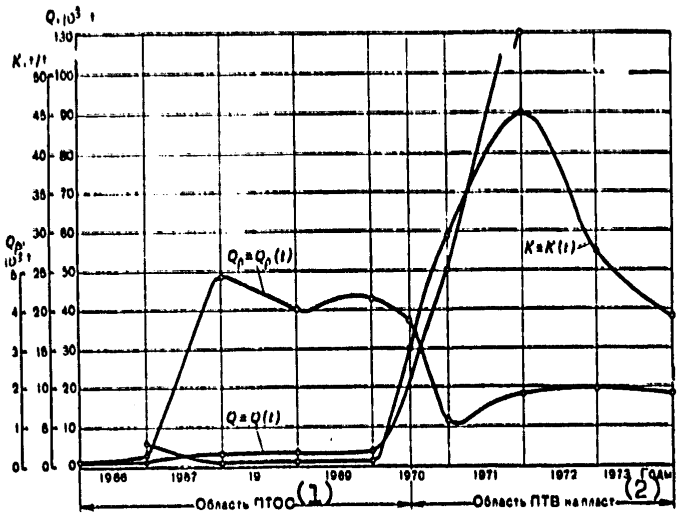

Figure 37. Results of effectiveness of PTOS and PTV in Section 2.
Key: 1. PTOS area 2. Area of PTV on bed

rapid penetration into the bottoms of the operating wells and the flooding of the output. Although during the period of continuous steam injection into the wells their flow rate initially showed a slight increase, nevertheless the process's effectiveness cannot be regarded as satisfactory, in view of the large expenditure of heat carrier and the deterioration of the technical and economic indicators. In all, 182,000 tons of steam were used during this experiment and a little more than 7,000 tons of oil were obtained.

Figure 37 gives comparative results for steam treatments and continuous areal injection. As is obvious from the data presented, the technical and economic indicators from continuous steam injection are considerably worse than those for steam treatments of the wells.

Theoretical calculations on the possible formation of the thermal front's outline were performed before the beginning of continuous steam injection. In theory, in the case of uniform movement of the heat carrier, in order to form a thermal front of about 45 m (of which 30 m is the steam zone and 15 m is the steam condensate zone), it would have been necessary to feed 41,000 tons of steam into well 257 over a period of 260 days, while to enlarge the thermal front to 52 m (an increase of 7 m) it would have been necessary to inject double that amount of steam into the bed and add 280 days to the process. In

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accordance with the calculations, 81,000 tons of steam were injected into the bed over a period of 540 days.

As has already been mentioned, actual field research showed that it was impossible to establish any stable front of heat carrier movement under conditions of acute irregularity of the reservoir. By the end of the experiment, steam condensate had been detected in wells located at a considerable distance (400-500 m) from the injection point (see the diagram in Figure 36). The actual diagram of heat carrier flows is shown in Figure 27.

In order to implement the recuperation process and obtain additional scientific information, cold water was fed in through steam injection well 257, in accordance with the calculations. Here the object of the exercise was undoubtedly to displace the thermal column because of the heat accumulated in the bed.

The goal of the field experiment under discussion was to determine the effect of the type of displacing heat carrier (superheated steam and cold water) and the sequence of its injection into the bed on the location of the maximum temperature profile point relative the middle of the bed's thickness (along the vertical). It was calculated that in order to remove the accumulated energy in the bottom zone of the well, which had reached a total of 6.35 million Gcal, it was necessary to pump about 35,000 m^3 of cold water into it.

Cold water injection actually took place over a period of 150 days, instead of the 170 days specified by the calculations, at an average daily injection rate of 195-200 m^3. During both the steam and cold water injection periods a complex of thermohydrodynamic investigations was carried out for the purpose of regulating and predicting the further course of the steam action process. In time, the temperature profiles that were taken for some wells and the isotherm and isobar maps made it possible to recognize the development of the process with respect to area and to make the correct decision for further action on the bed.

Figure 38 shows the results of this experiment in injecting steam and then injecting cold water, while Figure 35 contains the combined temperature profiles that were subsequently measured in observation well 477, which is located 100 m to the northwest of injection well 257, during the entire time the experiment was being carried out. The first profile was taken after the annual injection into the bed of superheated steam at a rate of 180 tons/day; during this time the temperature maximum reached 35°C (as opposed to the bed's natural temperature of 30°C), and its location corresponded to the middle of the bed's thickness.

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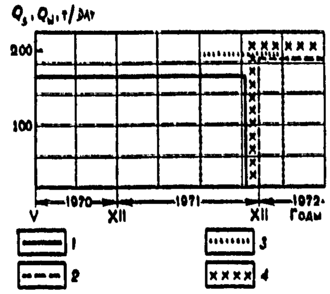

Figure 38. Data on the movement of the thermal column after cold water injection. Injection of: 1,2. steam and water into well 257; 3. steam into well 258; 4. water into well 454.

During the month's cessation of injection well activity and the transfer of steam injection to well 258 (100 m west of well 257) at a rate of 190 tons/day and well 454 (200 m north of it) at a rate of 200 tons/day, the formation temperature in the area of the observation well dropped to almost its natural level (31°C). After the injection of cold water into well 257 (into the preliminarily heated bed), the temperature at the bottom of well 477 first rose 5°C, and after a month had increased to 44°C. At the same time, as is obvious from Figure 35, the point of the temperature maximum shifted into the roof of the bed by approximately the distance of the latter's thickness (the process of intensive heat losses had begun). Soon after the cessation of cold water injection (in connection with the absence of an effect), the point of the temperature maximum again occupied a position in the middle of the bed's thickness, and for a long time the temperature then stayed approximately at the 38°C level.

No less interesting were the results obtained for observation well 476. During the injection of steam into well 257, the temperature at the bottom of well 476 reached 43°C, and before the injection of cold water into well 257 it remained almost unchanged. Thirty days after the beginning of thermal front displacement by the cold water, the temperature at the bottom of well 476 increased to 50°C, and 27 days later it had risen to 53°C. Then, in connection with the advance of the cold water, the well-bottom temperature began to drop gradually and by the end of the experiment had reached the normal formation level. Figure 34 shows the thermogram of well 476 during the periods of steam injection into well 257 and the displacement of the thermal column by cold water.

The experiment that was performed with alternating injection of superheated steam and cold water into the bed showed that this technique of creating a thermal column and moving it in the bed can prove to be effective under certain simpler geological conditions, provided that the temperature maximum is maintained in the center of the bed, primarily through regulation by the injection of cold water (on the side of its appropriate limitation, obviously). A comparison of the results of these two

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technologically different processes for acting on a bed showed that for complex geological conditions, the creation of a steam effect on the bed that is limited in area (PTOS is included in this category) is more effective. Thus, it has been established that for the given conditions, areal action on broad zones of a bed is insufficiently effective (although from the specific example that has been presented it is obvious that the effect actually was positive) and that for other and simpler geological conditions, the described method can prove to be highly effective.

Summing up the results of extended continuous steam injection for both beds, it can be stated that the heat carrier advances easily in a bed through the highly permeable channels in a macroporous reservoir, to considerable distances from the injection well. In connection with this, it was not possible to create any stable thermal front with outlines that were close to the calculated ones. In addition to this, frontal displacement of the oil in the bed was not insured.

Thus, when both micro- and macroporous reservoirs are present at the same time, continuous steam injection for the purpose of displacing oil from a porous reservoir does not prove to be effective.

Therefore, it is necessary to have a technological process for developing a deposit with the help of a steam effect that would make it possible to use naturally occurring highly permeable channels both to supply the heat carrier in order to displace the oil from a microporous reservoir, and for the free movement of the displaced oil to the operating wells.

The experiments on continuous injection of steam into a bed, the displacement of the thermal column with cold water, the results of numerous PTOS's, and the complex of geological, lithological, geophysical, physical, and -- finally -- thermohydrodynamic studies that were made served as a basis for the development of a fundamentally new technological process for steam action on a bed. It is called the cyclic-block steam action process (BTsPV), and its implementation proved to be highly effective. The results of an industrial experiment using this process are presented below.

Experimental-Industrial Projects Using Cyclic-Block Steam Action on a Bed

The idea of using this method arose during production work on the thermal intensification of oil extraction and the determination of the effectiveness of various technological processes

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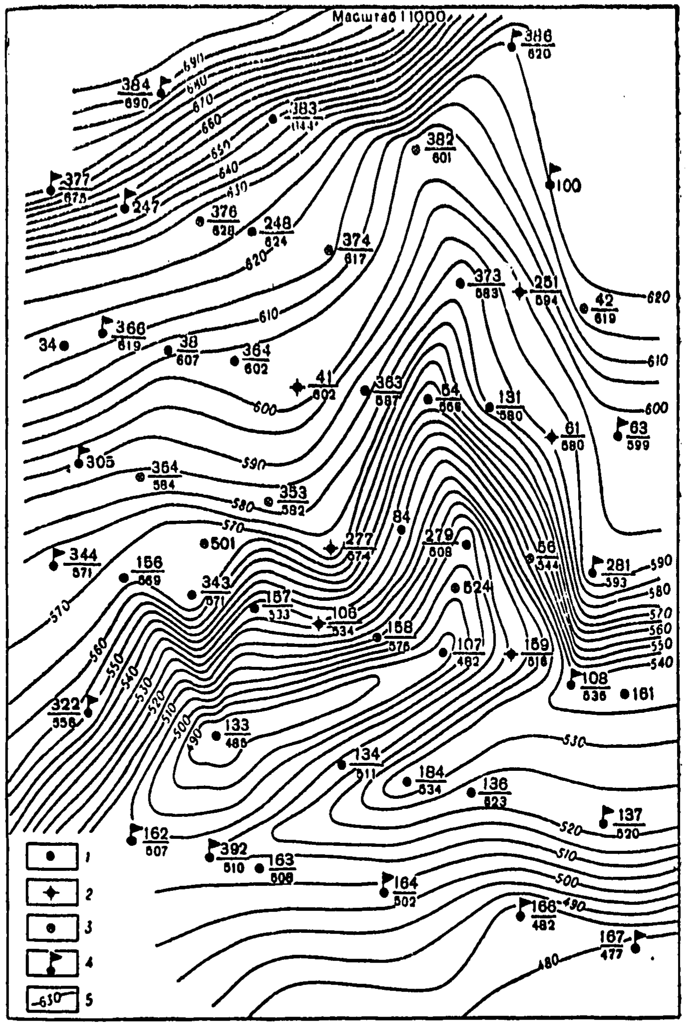

Figure 39. Actual diagram of well locations in second phase of BTsPV on a bed. Wells: 1. operational; 2. steam injection; 3. abandoned; 4. observation; 5. isohypses along roof of monolithic carbonaceous deposits.

under specific geological conditions. Previous attempts to conduct such experiments had been made, but it was not possible to determine their effectiveness, for various reasons. Taking this into consideration, in the area a section was chosen that

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had a sufficient number of operating wells to carry out the steam injection process and extract the necessary amount of oil from the reacting wells, as well as for the conduct of an entire complex of temperature investigations.

For this purpose, all the necessary investigative work was performed in a large stratigraphic trap in the central part of the Zybza deposit and the outlines of the section where BTsPV was to be conducted were delineated.

Figure 39 is a diagram of the location of the wells for BTsPV. The block contains existing operating wells (wells 41, 61, 63, 84, 131, 134, 159, 163, 164, 184, 251, 343, 364, 107, 54, 279, 373, 133), as well as abandoned wells 42, 281, 108, 136, 162, 501, 353, 382, and 374, which were to be used as observation wells. Here the average formation pressure did not exceed 12-15 kg/cm^2.

In the lithological sense more than anything else, a section of this deposit is represented by sharply expressed micro- and macroporous reservoirs. During the initial period of development, the basic oil extraction was from the macroporous reservoir. Below we present the technique used and the results of the experiment.

For comparison with the results of BTsPV and the evaluation of this method's effectiveness, a series of PTOS's were carried out in the experimental section. Before the experiment began, the average daily amount of oil obtained from the wells listed above was 10-12 tons.

On the whole, 13,900 tons of steam were used in the treatments and 6,000 tons of oil were obtained, for a steam-oil factor of 2.2 tons/ton. In Figure 40, the results of the evaluation of the PTOS's effectiveness are presented in the form of additional oil extraction. On the average, 1,390 tons of oil were obtained per well treatment.

Thus, control data characterizing the effectiveness of one of the technological processes were obtained from the actual experimental block.

After the appropriate control thermohydrodynamic investigations were completed, BTsPV work was begun on the bed according to the previously explained technological process. The goal of this work was to guarantee the formation of relative stable boundaries for the thermal field's front, which would insure a capillary impregnation effect and displace the oil from the microporous reservoir into the macroporous one. Besides this, the heat carrier -- just as the displaced oil was -- was

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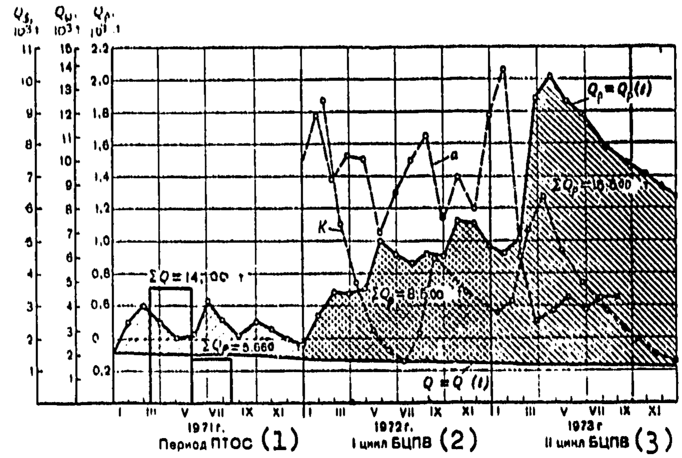

Figure 40. Effectiveness of PTOS and BTsPV.
Key: 1. PTOS period 3. BTsPV cycle II
2. BTsPV cycle I

directed to the central wells (373, 54, 279, 107, 133), which were located in the elevated part of the stratigraphic trap. The flow rates from these wells ranged from 2 to 2.5 tons/day. Because of its low productivity, well 133 was abandoned in 1959.

Wells 184, 343, 164, 163, and 84 were designated for the injection of steam, and the first cycle of steam action on the block was implemented with their help. They were used to feed 16,500 tons of steam into the bed, and 8,500 tons of oil were obtained in 1972. Before the beginning of the second BTsPV cycle, the steam-oil factor had reached 1.9 tons/ton. In connection with this, the wells in the block -- as is obvious from Figure 40 -- continued to operate with increased flow rates.

The second BTsPV stage was carried out through other operating wells located down the dip of the bed. In connection with this, it was proposed that the direction of the thermal flows be changed and that previously unheated sections of the block be acted upon in order to avoid breakthrough of the heat carrier. In order to accomplish this, six operating wells (41, 61, 106, 159, 251, and 277) in the western and eastern parts of the block were chosen; during the first period of BTsPV operations, these wells had served as operational-observation wells. PTOS's had previously been carried out in them, with differing results. At the time steam injection was begun, their flow rates were 0.5-1 ton/day of oil. In order to evaluate the effectiveness of the second BTsPV cycle in comparison with the first one, careful thermohydrodynamic investigations

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Table 19.

Номер скважины (1)	Начало и конец нагнетания, 1973 г. (2)	Количество нагнетаемого пара, т (3)					Суммарное количество нагнетаемого пара, т (4)	Давление нагнетания на устье, кгс/см² (5)	Температура на устье скважины, °C (6)
		I	II	III	IV	V			
150	20/I—11/IV	300	2500	4700	1500	—	9000	12—28	210
61	21/II—04/V	—	750	2200	2400	650	6000	11—28	200
106	27/II—04/V	—	250	1750	2500	—	4500	20—27	210
251	01/III—04/V	—	—	3250	3100	650	7100	10—30	200
277	12/III—04/V	—	—	3900	3000	600	7500	18—30	210
41	03/IV—04/V	—	—	—	5200	850	6050	11—28	200
Среднемесячные показатели (7)			450	510	590	680			

Key:
1. Well number
2. Beginning and end of injection, 1973
3. Amount of steam injected, tons
4. Total amount of steam injected, tons
5. Injection pressure at well mouth, kg/cm^2
6. Well-mouth temperature, $^{\circ}$C
7. Average monthly indicators

were carried out in all the operating, idle and abandoned wells before the process was begun. Steam injection into the block continued for about 4 months. Depending on the nature of the operating wells' performance and the degree of their reaction, appropriate regulation of the steam injection and operating wells' parameters was implemented. On the average, each of the wells received 6,000-9,000 tons of steam at a well-mouth pressure of 10-30 kg/cm^2 and a temperature of 210°C. The bed received an average of 600 tons/day of steam through the system of wells, with about 40,000 tons of steam being fed into it during the second cycle. Table 19 gives the average monthly indicators of the work done through the steam injection wells.

The operating wells began to react relatively quickly, in 15-20 days. This reaction was registered as a drop in the mineralization of the extracted formation water, which was caused by the advance of the steam condensate through the macroporous ducts, an increase in the temperatures at the bottoms of the operating wells, and an increase in their oil flow rates. These parameters were the main ones, and careful observations were made of any changes in them. Besides this, in order to maintain the dissolved gas conditions measures were taken so that the amount of liquid removed was greater than the amount of steam condensate and formation water that entered the block.

After 2 months, the temperatures at the bottoms of the operating wells had increased from 30 to 50°C, while 5 months after

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the beginning of the process, the well-bottom temperatures averaged 50-75°C.

The oil flow rates increased for all the wells in the entire block, and abandoned well 133, which was located in the highest part of the deposit, went into operation with a flow rate of 25-30 tons/day of waterless oil. For wells 54, 107, 135, and others, the extraction rate increased from 1-2 to 15-25 tons/ /day.

A characteristic feature of the operating wells' performance was that these high oil removal rates occurred as only insignificant depressions (no more than 1 kg/cm²) were being created in the bed. During the second BTsPV operation, the implementers not only succeeded in directing the thermal flow in the given direction (toward the central wells), but also managed to create a stable thermal field inside the block under discussion. Although high temperatures -- sometimes reaching 90-100°C -- were recorded for all the operating wells located between the two rows of steam injection wells, the well-bottom temperatures practically did not change for the observation, idle and abandoned wells located even in close proximity to the steam injection wells. The results of the temperature measurements for the steam injection, operating and observation wells will be presented later. Thus, the main goal of the process -- to create a stable thermal front in a local section -- was achieved. For all practical purposes, all the heat fed into the bed was used within the limits of the given block. This is indicated by the relatively high temperatures occurring at the time at the bottoms of the existing operating wells (65-70°C), which points to the maximum use of the thermal energy expended to heat up the rock in the bed and the ongoing recuperation process.

Calculations of heat losses into the roof and the floor along the well shaft are usually presented in theoretical works. Actually, these losses occur during any thermal process, but they increase to a considerable degree in beds represented by micro- and macroporous reservoirs when a heat carrier injected into the bed cannot be localized because of its "leakage" through highly permeable ducts. In connection with the impossibility of regulating the process, such heat losses took place during the continuous injection of steam in the Zybza deposit, as a result of which there was not only a decrease in the effectiveness of the work being done, but the unsoundness of implementing this technological process was also established. Therefore, one of the advantages of cyclic-block steam action on a bed is a significant reduction in heat losses. In view of the fact that until now there has not even been an approximative

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technique for evaluating these losses under the conditions encountered in a fractured-porous reservoir, it is necessary to devote special investigations to this question, which is of great practical importance.

Figure 40 gives the results obtained for the two BTsPV operations on the bed, in comparison with the PTOS's that were also performed in this section (block). Without diminishing the role of PTOS as a means for increasing oil output and effectively working the reservoir of the bottom zone of wells, a new technological process that makes it possible to exploit a porous reservoir was developed as the result of the use of BTsPV on the bed. By comparing but not contrasting these two methods and starting with the fact that the use of one variant does not preclude the use of the other (particularly during the initial period of well and deposit development), a logical relationship was established between them. In connection with this, the possibilities of PTOC as a method for increasing the oil yield of a bed in the bottom zone of wells was evaluated, along with those of BTsPV as a method featuring extensive envelopment of the bed by the heat carrier and as a means for developing deposits with anomalously viscous oil with a high final oil yield from the bed. As the result of PTOS, 6,000 tons of oil were obtained from the wells in this block: on the average, 1,390 tons of oil were taken from a single well, with a steam-oil factor of about 2.5 tons/ton. Average daily oil extraction was increased from 10 to 25-30 tons, although before the beginning of BTsPV it had again dropped to 10 tons.

After the first BTsPV operation, when 16,500 tons of steam were injected into the bed, 8,500 tons of oil were obtained from the wells in the block. The average daily oil yield of these wells increased from 10 to 40 tons, then by the end of the period dropped to 20-25 tons. During the entire period of exploitation after the first BTsPV operation (1 year), the average steam-oil factor was 1.85 tons/ton.

During the implementation of the second BTsPV operation, about 40,000 tons of steam (triple what was injected during the first cycle) were injected into the bed. As a result of this second operation, oil extraction from the block increased to 80 tons/ /day; that is, it increased by a factor of 8-10. As oil extraction increased there was a reduction of the amount of water in the extracted output. A relationship was established between oil extraction and the amount of liquid, as a whole, removed from the block. As the amount of liquid removed increases, so does the oil output. Separate disruptions that lowered the oil yield took place primarily for technical reasons. On the whole for the two operations, 24,500 tons of oil were obtained for a steam-oil factor of 2.6 tons/ton. The average

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Table 20.

Операция (1)	Число охваченных скважин (2)	Закачано в пласт пара, тыс. т (3)	Добыто дополнительной нефти, тыс. т (4)	Дополнительная добыча нефти на одну скважину, т (5)	Паронефтяной фактор, т/т (6)
ПТОС (7)	10	14,1	5,66	1390	2,5
БЦПВ (8)	12	56,5	24	2000	2,3
первый цикл (9)	8	16,5	8,5	1050	1,85
второй цикл (10)	10	40,0	15,5	1550	2,6

Key:
1. Operation
2. Number of wells encompassed
3. Steam injected into bed, tons x 1,000
4. Additional oil extracted, tons x 1,000
5. Additional oil extraction per well, tons
6. Steam-oil factor, tons/ton
7. PTOS
8. BTsPV
9. First cycle
10. Second cycle

steam-oil factor for the two cycles of action in the block was 2.3 tons/ton.

Table 20 shows the comparative indicators of the block's development when PTOS and BTsPV were used.

The good results obtained after the use of BTsPV, both for individual wells and the block as a whole, showed that as the result of the implementation of this process, oil was successfully displaced from the microporous reservoir into the macroporous one. One characteristic feature is that the movement of the oil through the highly permeable ducts in the macroporous reservoir took place for rather low gas factors -- 2 m^3/ton. Although this energy of the dissolved gas in the only slightly permeable reservoir, saturated with high-viscosity oil, did not play a particularly important role (for all practical purposes) because of the high capillarly resistance forces, in the highly permeable reservoir it takes on special importance and is the main motive force of the oil in the bed.

Later, even when there was a significant drop in the temperatures of the bed and the gas-water-oil liquid back to their normal levels, the oil's mobility remained high. It is sufficient to say that the wells in the block that had high flow rates were exploited with extremely insignificant depressions in the bed that reached only 0.05-0.1 kg/cm^2.

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Thus, we have seen the practical implementation of the idea of displacing oil from a porous, undeveloped part of a reservoir with envelopment of significant volumes of the oil-saturated rock in the bed that were impervious to displacement by PTOS under the specific conditions that existed, since PTOS has a limited zone of bed development.

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CHAPTER 9. RESULTS OF EXPERIMENTAL INDUSTRIAL WORK ON STEAM ACTION ON A BED

[Text] Steam Action in Combination With Flooding in the Oil Fields on Sakhalin Island

On Sakhalin Island the basic reserves of high-viscosity oils are concentrated in the Okha, Katangli, Uyglekuty, Vostochnoye Ekhabi, and Zapadnoye Sabo deposits.

The development of beds under natural conditions, as well as with the use of other nonisothermic methods, did not prove to be very effective. The oil yield for most of the deposits has not exceeded 20 percent, despite the length of the period they have been under development (more than 40 years).

The injection of steam into the bed for frontal displacement of the oil was begun in 1968, in the Okha deposit, and then in the Katangli and Vostochnoye Ekhabi deposits.

The Okha deposit is confined to a brachyanticlinal fold that is complicated by numerous faults and reversed faults, with latitudinal and diagonal strikes, that form 10 blocks in which the oil pools of beds 3, 4, 7, and 8 have their outlines. More than 80 percent of the oil is contained in these beds, the average oil-saturated thickness of which is 22-36 m. The beds consist of slightly cemented sand and lie at depths of 100 to 950 m. Their porosity is 27 percent and their permeability is about 1,500 md. The density of the oil is 0.92-0.95 g/cm^3.

In 1968, a production plan for the development of an experimental section (Block 9, Bed 4) was drawn up. On the basis of the experimental industrial work that was done, a production plan for the development of the basic productive beds in the Okha deposit was formulated in 1971.

The plan provided for the displacement of the oil by a fringe of steam moved by unheated water. Three separate development

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Table 22.

Показатели (1)	Годы (2)							
	1969	1970	1971	1972	1973	1974	1975	1976
Добыча нефти по месторождению Центральная Оха, тыс. т: (3)								
с нагнетанием пара и заводнением (4)	147,4	171,6	196,1	223,6	240,8	254,0	270,0	250
(5) без нагнетания пара и заводнения	100,7	98,2	97,8	94,5	82,7	75,9	75	75
Объем закачки пара, тыс. т (6)	156,0	245,7	363,1	471,3	648,6	635,1	630	750
Объем закачки воды, тыс. м³ (7)	25,8	154,9	274,0	415,5	539,7	722,9	810,2	990
Фонд скважин: (8)								
(9) эксплуатационных	793	824	805	824	821	807	829	830
(10) нагнетательных	19	27	42	52	58	83	86	81
Себестоимость добычи 1 т нефти, %: (11)								
с нагнетанием и заводнением (4)	100	103,7	100,7	93,0	107,3	117,4	121,9	110,6
(5) без нагнетания пара и заводнения	100	104,2	105,0	106,2	114,3	121,9	131,0	123,1
Годовой экономический эффект, тыс. руб. (12)	1043	1465	2231	3378	3046	2992	3442	3812

Key:
1. Indicators
2. Years
3. Oil extraction from Tsentral'naya Okha deposit, tons x 1,000
4. With steam injection and flooding
5. Without steam injection and flooding
6. Volume of steam injected, tons x 1,000
7. Volume of water injected, m^3 x 1,000
8. Number of wells:
9. Operational
10. Observation
11. Cost of extracting 1 ton of oil, %:
12. Annual economic effect, rubles x 1,000

sites were chosen: Bed 3, Bed 4, and Beds 7 and 8 combined. The volume of the steam fringe was to be 30-50 percent of the volume of the pores in the bed, depending on the well placement density. Development of the deposit using the steam fringe would make it possible to achieve a final oil yield of 52 percent of the initial balance reserves for a specific steam consumption rate of 2.0 tons/ton.

At the end of 1975, sections of the Okha deposit containing on the order of 26.4 percent of the field's total reserves were put under development by combined action on the bed.

The basic indicators of the development of the Tsentral'naya Okha deposit are shown in Table 22.

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Table 23.

Показатели (1)	1970 г.	1971 г.	1972 г.	1973 г.	1974 г.	1975 г.	1976 г.
(2) Добыча нефти, тыс. т	29,57	28,95	32,62	32,70	46,25	42	81
Дополнительная добыча нефти, тыс. т (3)	13,70	14,69	18,40	17,11	30,44	45	55
Закачка пара, тыс. т (4)	56,71	52,12	59,86	74,29	87,34	76	105

Key:
1. Indicators
2. Oil extraction, tons x 1,000
3. Additional oil extracted, tons x 1,000
4. Steam injected, tons x 1,000

In 8 years, the introduction of steam action in combination with flooding in the Sakhalin deposits made it possible not only to stabilize the extraction of oil, but to increase it. In 1975, oil extraction from Sakhalin deposits developed with steam action was about 25 percent of the entire amount produced by the Sakhalinneft' association.

By 1 September 1975, the accumulated volume of steam injected into the bed was 2.99 million tons, while about 2.7 million m^3 of water had been injected. At the present time, the rate of water injection exceeds the steam injection rate.

At the Katangli deposit, steam injection into the bed began in 1969, in an experimental 14-ha section in Block 1 Bed 1. The deposit is confined to an anticlinal fold complicated by dislocations. Beds 1, 2 and 3 contain commercially exploitable quantities of oil and consist of unconsolidated sands. The depth of occurrence is 80-150 m, the oil-saturated thickness is 18-35 m, the porosity is 29-32 percent, the permeability is 3.85 d, the degree of oil saturation is 71-75 percent, the oil's viscosity is 2,000 cp at the bed's temperature of 7°C, and the density of the oil is 0.936 g/cm^3.

During the previous 40 years of exploitation the oil yield factor was about 14 percent and the amount of water in the oil reached 80 percent for a network of wells ranging from 1.2 to 2.0 per hectare in density. The deposit's regime is gravitational, with slightly active outline water.

The basic technical and economic indicators for the development of Block 1 Bed 1 of the Katangli deposit are shown in Table 23.

Over the entire period, 529,200 tons of steam were injected and an additional 195,400 tons of oil were extracted.

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By the beginning of 1977, a total of about 2 million tons of oil had been obtained on Sakhalin Island through the use of thermal methods of affecting the bed.

Steam Action in the Yaregskoye Field

The Yaregskoye field consists of a thick, sloping bed of productive sandstones that is confined to Middle Devonian deposits of the Givetian stage and occurs at a depth of 180-200 m. The bed is characterized by the following indicators: thickness -- up to 30 m; permeability -- up to 3-5 d; porosity -- up to 24 percent; initial formation pressure -- 15 kg/cm^2; temperature -- 6°C. The oil's viscosity at the bed temperature is 11,000-15,000 cp, while the density of the degasified oil is 0.96 g/ /cm^3. The bed's oil-saturation coefficient is 0.42-0.98. Numerous fissures with a shift magnitude of up to 6-8 m divide the deposit into tectonic blocks 10-30 m in size.

Three stages can be distinguished in the field's development: experimental exploitation from the surface, development by the shaft method, and development by the shaft method in combination with thermal action on the bed. Experimental exploitation from the surface, with a distance between wells of 70-100 m, showed that the bed's oil yield factor was low. This served as grounds for the development of the field by the shaft method.

Since 1939, three shafts have been in operation in the Yaregskoye field. Two systems are utilized in development by the shaft method: the Ukhta system, in which the pool is drained by an extremely dense network of wells (12-20 m apart) up to 50 m deep that are drilled from workings in the overlying tuffite horizons, and the slanted-well system, where the gallery is located in the upper part of the bed and hexagons with an area of 8-12 ha are drilled out with slanted wells up to 200 m long. The latter system was introduced in this field in 1954. The transition to the slanted-well system made it possible to reduce the amount of mining work by two-thirds.

By the end of the 1960's, the oil yield factor had risen substantially for the existing shafts in the workings. The density of the well network in the bed was extremely variegated. The 30 years' worth of experience that has been accumulated during the development of the Yaregskoye field shows that maximum concentration of the well network, without any additional action to affect the bed, does not lead to an increase in the oil yield.

Considering the specific nature of the shaft conditions, the steam method of acting on the bed was used, beginning in 1968.

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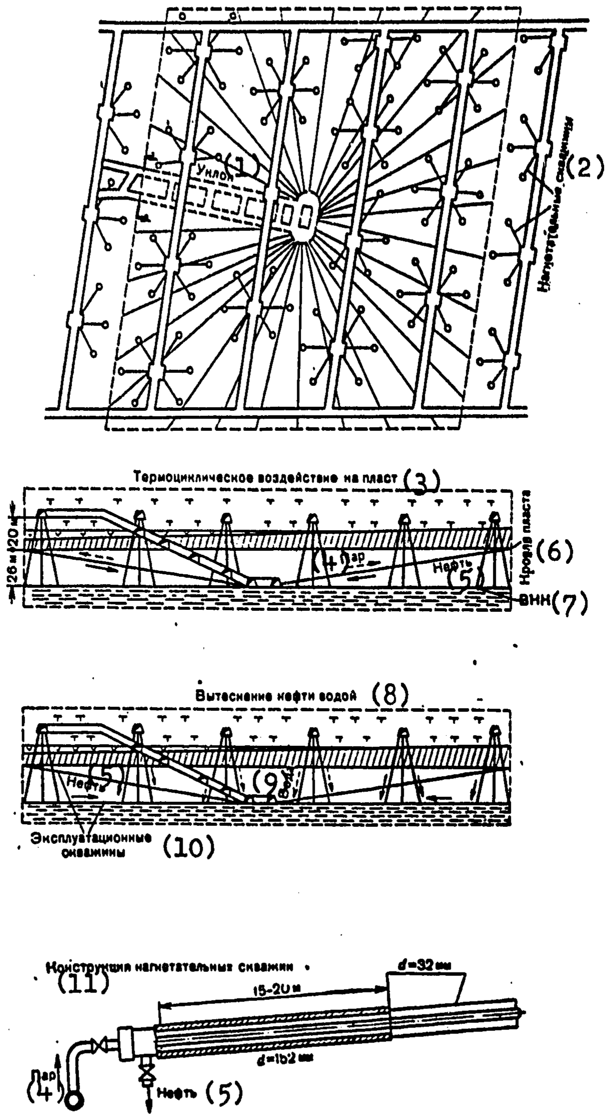

Figure 47. Thermal action on a bed under shaft conditions.
Key:

1. Slope
2. Injection wells
3. Thermocyclic action on the bed
4. Steam
5. Oil
6. Roof of bed
7. Water-oil contact
8. Oil displacement by water
9. Water
10. Operating wells
11. Design of injection wells

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During a 5-year period, a significant amount of experimental industrial work was done that made it possible, in 1973, to change over completely to development of the field by thermal methods. The first experiments were performed with the Ukhta system and a single injection well surrounded by operating wells at a distance of 2-20 m. Along with the positive results that were obtained, several flaws were discovered: there was a partial breakthrough of steam into the workings, which made it necessary to lower the injection pressure from 6-10 to 3-4 kg/$/cm^2$, and there was intensive sand erosion; the lower part of the bed was insufficiently heated because of dissemination of the steam throughout the upper part. Experimental work with bed heating and wells arranged in a dense network proved to be highly effective. For instance, one experimental section of 1.8 ha contained 63 injection and 71 operating wells. For a specific steam consumption rate of 3.5 tons/ton, an oil yield coefficient of close to 40 percent was obtained.

Simultaneously with the expansion of experimental industrial work utilizing the Ukhta system, testing of a two-level thermal action system was carried out. The essence of this development system is that steam is injected through a well in the tuffite horizon, while the oil is extracted through rising, slanting wells drilled from the slope, as shown in Figure 47.

Testing of this system showed that with two-horizon placement of the wells, it is possible to eliminate the basic flaws inherent in the Ukhta system and to achieve even better technological indicators. In view of this, all the areas undergoing thermal treatment began to be converted to the two-horizon system late in 1971 and early in 1972. This was accomplished by drilling slanting and rising wells into the bed from the slope.

The original operating site for the development process was a tilted block with an area of 10-15 ha and a network of 200-300 injection wells. During the 2.5-3 years of exploitation work, the average daily oil yield was 200 tons, the steam consumption rate was 2.5 tons/ton, and the oil yield coefficient was 40-50 percent.

When steam action was being used in the Yaregskoye field, it was discovered that improving the method of thermal action on the bed, as well as converting (at some stage) from the injection of steam to the injection of byproduct gas and then cold water makes it possible to lower the steam consumption rate to 2 tons/ton and achieve a final oil yield coefficient that exceeds 50 percent.

The steam action indicators for the Yaregskoye field are shown, by years, in Table 24.

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Table 24.

Показатель (1)	Годы (2)							
	1969	1970	1971	1972	1973	1974	1975	1976
Количество закачанного пара, тыс. т (3)	24,6	136,5	250,3	353,8	414	500	680	720
(4) Добыча нефти, тыс. т	5,0	17,6	48,1	91,2	130,2	172,4	247	280
(5) Площадь прогрева, га	3,2	17,3	20,7	38,5	56	87	100	120
Удельный расход пара, т/т (6)	4,9	7,8	5,2	3,2	3,2	2,9	2,8	2,1

Key:
1. Indicator
2. Years
3. Amount of steam injected, tons x 1,000
4. Oil extracted, tons x 1,000
5. Area heated, ha
6. Specific steam consumption, tons/ton

After steam action was used in the Yaregskoye field, a savings of 1.8 million rubles was achieved in 1973-1975 because of the growth in the current oil extraction rate and the increase in the oil yield coefficient, both of which were accomplished while the specific capital investments were lower.

As a result of the mastering of the new techniques, a general plan for the development of the Yaregskoye field was proposed that would make it possible to increase the annual yield from 250 tons [sic] in 1976 to 1 million tons. This level of productivity would be achieved in several stages. The first goal was the reconstruction of the oil shafts in order to increase their productivity to 400,000 tons.

Increasing Oil Extraction in Fields in Azerbaydzhan by Acting on the Bed With Heat Carriers

In Azerbaydzhan at the present time, there are 48 deposits, located in 10 fields in the Apsheronskaya Oil and Gas Province, in which the steam action process can be used. These deposits lie at depths that do not exceed 1,000 m and are characterized by geological data that are favorable from the viewpoint of exploitation. The sites have been picked out by a careful analysis of the basic indicators of the current state of development and the geological conditions.

Industrial tests of steam action on a bed by frontal displacement of the oil were begun in oil fields in Azerbaydzhan containing high-viscosity oil in 1969. The first experimental work was done in the Khorasany area of the Balakhano-Sabunchino-Romaninskoye field. This section covers an area of 55 ha. The PKS_v bed consists of sand lying at a depth of 400-600 m, and is

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Table 25.

Показатель(1)	1970 г.	1971 г.	1972 г.	1973 г.	1974 г.	1975 г.	1976 г.
Количество закачанного пара, тыс. т (2)	20,0	61,3	80,2	69,2	60,5	27,5	70
(3) Дополнительная добыча нефти, тыс. т	1,5	2,2	4,0	4,8	4,2	3,9	10
Удельный расход пара, т/т (4)	13,3	27,9	20,0	14,4	14,4	7,1	7,0

Key:
1. Indicator
2. Amount of steam injected, tons x 1,000
3. Additional oil extracted, tons x 1,000
4. Specific steam consumption, tons/ton

characterized by the following parameters: effective thickness -- 15 m; permeability -- 218 md; oil viscosity under bed conditions -- 55 cp; oil density -- 0.934 g/cm^3. The oil contains 30 percent asphalt tars and 1.26 percent asphaltenes. At the beginning of the steam action, the oil yield coefficient was 0.25. Steam injection into the northern part of the section was begun in April 1969, while in the southern part the process was started in December 1970.

The basic indicators of the steam action's effect on this section are given in Table 25.

About 400,000 tons of steam were pumped into the bed from 1969 to 1976, and the additional oil extracted amounted to 37,000 tons.

In January 1974 there was a changeover to the injection of cold water into this section, for the purpose of displacing the thermal fringe. From January 1974 to October 1975, about 47,000 tons of water were injected into the bed. During this period, the increase in this section's oil yield was about 3,500 tons, for an economic effect of more than 40,000 rubles.

The displacement of oil by steam was then practiced in a section of 59.2 ha that was located in the Binagady-Kirmakinskaya area. The first site chosen in this area was the KS_{5a+b} horizon, which has the following geological and exploitational characteristics: depth of occurrence of the bed -- 250-500 m; effective thickness -- 12.5 m; permeability -- 59 md; current oil yield coefficient -- 0.19; oil viscosity under bed conditions -- 30 cp; oil density -- 0.918 g/cm^3; asphalt tar content -- 30 percent; asphaltene content -- 1.2 percent.

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Table 26.

Показатель (1)	1972 г., август — сентябрь (2)	1973 г.	1974 г.	1975 г.	Всего за 2,5 года (3)	Среднегодовые показатели (4)
Количество закачанного пара, т (5).	5992	27 512	26 097	1873	61 474	19 210
Дополнительная добыча нефти, т (6).	—	781	291	622	1 694	529

Key:
1. Indicator
2. August-September 1972
3. Total for 2.5 years
4. Average annual indicators
5. Amount of steam injected, tons
6. Additional oil extracted, tons

Steam injection was begun in August 1972 and halted in January 1975.

The basic indicators of the results of the steam action are shown in Table 26.

Despite the cessation of steam injection, the operating wells located in the zone of thermal action continue to function with increased oil flow rates.

In the Kukhshana area, the steam action process was begun in January 1974. The area of the section is 29 ha. The productive bed lies at a depth of 610-660 m, and is characterized by the following parameters: effective thickness -- 18 m; permeability -- 10 md; oil viscosity under bed conditions -- 23 cp; oil density -- 0.915 g/cm^3; asphalt tar content -- 30 percent.

The increase in the oil yield for 10 months of 1974 (January to October) was 643 tons, which was achieved by injecting about 19,000 tons of steam.

On the whole, for all sites where steam action with frontal displacement of the oil in the bed has been or is being implemented, an increase in oil yield has been observed.

However, the effectiveness of the process was reduced considerably because of technical and geological complications, the main ones of which were:
1) an inadequate geological study and preparation of the site for the conduct of the indicated work;
2) intensive manifestations of sand in the operating wells;
3) a lack of reliable means for raising the output to the

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surface;
4) an inadequate amount of circulating fresh water for heat carrier production, and others.

These causes lead to frequent disruptions in the process. In connection with the cessation of steam injection, the heat carrier cools because of the transfer of heat into the rock and loses its value as a thermal factor. Later resumption of the steam injection process leads to additional heat consumption, which reduces the process's effectiveness and raises the cost of an additionally extracted ton of oil. Besides this, when the continuity of the supplying of the heat carrier is disrupted, the drop in pressure and temperature causes a reversed movement of the condensed hot water toward the bottom of the steam injection well, and it carries a great deal of sand with it. Field observations have established that under the conditions present in the oil fields in Azerbaydzhan, the reservoirs of which consist of weakly cemented, unconsolidated sand, sharp fluctuations in the thermal regime of a bed cause intensive disruption of the bonds between the grains of sand and intensify plug formation in the wells.

Steam Action in the Kenkiyak Field

The Kenkiyak deposit is confined to an asymmetric brachyanticlinal fold that is split into four fields by tectonic dis tions. The steam action process was used on the Middle Jurassic terrigenous productive horizons 2 and 3, which lie at a depth of 300-350 m and consist of a frequently alternating sequence of sand, sandstone, aleurites, and clay rock. The deposit is characterized by the following parameters: oil-saturated thickness of the bed in the experimental section -- 25.7 m; porosity -- 30.5 percent; permeability -- 4 d; degree of oil saturation -- 72 percent; oil viscosity at 20°C -- 180 cp; oil density -- 0.915 g/cm^3.

VNIIneft' [All-Union Scientific Research Institute of Petroleum and Gas] drew up a process plan for the experimental section in 1968, and for the entire deposit in 1972. The plan provides for displacement of the oil by a fringe of steam (totaling 56 percent of the pores' volume) moved by cold water. The implementation of the steam action project will make it possible to achieve an oil yield of 44 percent for a specific steam consumption rate of 2.0 tons/ton.

The basic actual indicators of the development of the experimental section in the Kenkiyak deposit (Aktyubinskaya Oblast) are shown in Table 27.

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Table 27.

Показатель (1)	1973 г.	1974 г.	1975 г.	1976 г.
Количество дополнительно добытой нефти, тыс. т (2)	5,6	20,5	45	50
Количество закачанного пара, тыс. т (3)	13,4	47,2	105	110
Удельный расход пара, т/т (4)	2,4	2,3	2,2	2.3

Key:
1. Indicator
2. Amount of oil additionally extracted, tons x 1,000
3. Amount of steam injected, tons x 1,000
4. Specific steam consumption, tons/ton

Active introduction of the steam injection method began at this deposit in 1973.

Four years after the introduction of the steam method, the injection of about 275,600 tons of steam has resulted in the extraction of more than 121,100 tons of oil. A total of four injection wells are in operation, while the plan provides for 10 injection wells. Further realization of the planning recommendations will primarily require an increase in the number of steam generators (three are now in operation), as well as the implementation of a complex of measures to combat the erosion of sand from the wells as the result of disruption of the zones near the bottoms of the operating and injection wells.

Utilization of Heat Carriers During the Development of Oil Fields Containing Low-Viscosity Oil

Recent field tests have shown that beds containing relatively low-viscosity oils can also be developed with considerable effect by the use of steam action. Thus, the exploitation of significant residual reserves of low-viscosity oil by injecting heat carriers into the bed is a matter of extreme interest.

In our country, the study of the applicability of heat carriers in the development of deposits containing low-viscosity oil was begun by scientists and specialists in the Ukrainian SSR working at UkrgiproNIIneft' and the IG [Institute of Geography] and GGI [Mining and Geological Institute] of the Ukrainian SSR Academy of Sciences. These institute proposed two methods for affecting a bed with heat: 1) a composite method for thermal action on a bed; 2) the injection of water with high thermodynamic parameters (temperature -- 320-340°C, pressure -- 160-220 kg/cm^2) into the oil-saturated bed.

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The second method is based on the fact that given the thermodynamic parameters listed above, water -- despite its physical properties -- is a good solvent for oil; that is, the displacement mechanism is based on the effect of dissolving the oil.

Unfortunately, the second method has still been tested only under laboratory conditions. Its testing under field conditions has been delayed because of a lack of the appropriate technical facilities.

The essence of the first method is that the process of affecting the bed is carried out in two stages. During the first stage, a high-temperature zone (hot fringe) of a certain size (25-50 percent of the bed's volume) is created around the injection well by injecting a heat carrier. In the second stage, cold water is injected in the forced mode. When the water strikes the steam zone, it carries heat into the depths of the bed and is partially changed to steam itself. Filtration of the two-phase mixture in the bed increases the range of the process with respect to both area and depth, as a result of which there is fuller treatment of the bed with heat and, consequently, more nearly complete displacement of the oil.

The composite method of thermal action on a bed has already been tested under field conditions in beds containing low-viscosity oil. An industrial experiment was organized for the MEP section of the Borislavskoye deposit, which contains oil with a viscosity of 5-7 cp. The experimental site in this section is composed of Yamnenskiy horizon sandstones and lies at a depth of 450-500 m. Since 1971, an industrial experiment in thermal action with transfer of the hot zone by cold water has been in operation on a large scale in this section. The preliminary results of the experiment showed that the steam-oil factor is 2-3 tons/ton, and it has also been established that the composite injection method may result in an increase in oil extraction of several hundred percent. The well's flow rates increased by factors of 3-8, which is a significant improvement in the economics of the oil extraction process.

On the basis of the results obtained in the MEP section, UkrgiproNIIneft' drew up plans for steam action in combination with flooding on the Yamnenskiy horizon of the Urichskoye deposit and in the Stryyskoye sediments in the Miriam section of the Borislavskoye deposit.

According to calculations made by K.A. Oganov, extensive introduction of the steam action method in small deposits in the Ukrainian SSR that have been under development for a long time will make it possible to extract hundreds of thousands of tons of additional oil every year.

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PART 2. DEVELOPMENT OF A DEPOSIT USING INTRABED COMBUSTION

CHAPTER 1. FEATURES OF INTRABED COMBUSTION AS A THERMOCHEMICAL METHOD OF DEVELOPMENT

[Text] The thermal method of oil extraction, using intrabed combustion, is intended to act on the bed as a whole. Priority in the proposal and realization of this method belongs to the Soviet Union [39].

The essence of this process is as follows. Initially, the conditions necessary for the initiation and formation of a stable combustion front are created in the zone near the bottom of the ignition well. Well-bottom fuel burners, electric heaters, chemical reagents, and so on are used for this operation. After the combustion front is formed, an oxidizing agent (air, oxygen-enriched air or a gaseous mixture containing oxygen, and so on) is injected into the bed from the surface in the amount necessary to maintain the thermochemical reaction and move the combustion front through the bed. In connection with this, part (15 percent) of the oil in the bed burns, while the liberated fuel acts on the bed and facilitates displacement of the oil from it. The products of the process (oil, combustion gasses, hydrocarbon gasses, water) are extracted through operating wells.

Two basic variants of intrabed combustion are distinguished: direct flow and counterflow. In the former, bed ignition and the injection of the oxidizing agent are performed through the same well. The oxidizing agent flow and the combustion front move in the same direction, away from the ignition (injection) well and toward the operating ones.

In the counterflow variant, the bed is ignited and the oxidizing agent is injected through different wells. When combustion is initiated in the ignition well, the oxidant is fed in through the injection well into the oil-saturated, unheated part of the bed, in a direction opposite to that of the moving combustion nucleus. The products of the process (gasses, steam

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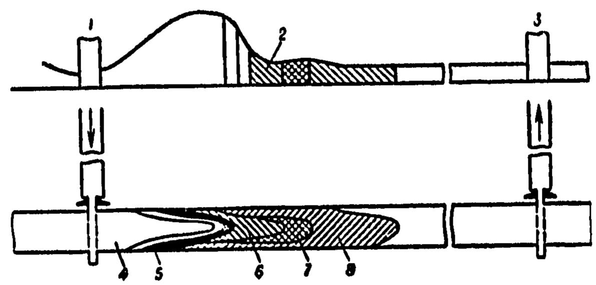

Figure 48. Propagation of intrabed combustion: 1. injection well; 2. steam plateau; 3. operating well; 4. compressed zone; 5. combustion front; 6. steam zone; 7. surge of hot water and light hydrocarbons; 8. surge of oil.

and oil) move through the burned zone toward the ignition well, which becomes an operating well, and are extracted to the surface. The basic reason for the development of this method was the practical impossibility of realizing the direct-flow process in deposits containing immovable oil (or bitumens).

There are also variants in which intrabed combustion (VG) is combined with other thermal methods. VG can also be used to affect the zone near the well bottom.

Temperature dissemination takes place in the form of a thermal wave with a steep falloff in the direction of the air current ahead of the front and a gradual decline behind the combustion front. As the combustion front moves in the bed, several temperature zones form, as shown in Figure 48. The temperature in the combustion zone can reach 400°C or higher. At such a temperature, the liquid in the combustion zone evaporates completely. The heavy fractions of the oil settle out onto the surface of the grains in the form of a coke residue. This part of the oil also serves as fuel.

A steam zone forms ahead of the combustion front, and within its limits the temperature drops to 93-204°C. Ahead of the steam zone there is condensation of the oil and steam and a fringe of hot water and light hydrocarbons forms. Finally, an oil surge with a temperature equal to the original bed temperature forms ahead of the surge of hot water and light hydrocarbons.

The temperature reached during the movement of the combustion front determines the heat transfer and oil displacement mechanism. The mechanism of oil displacement by steam and hot water

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predominates in the steam and hot water zones, while displacement by mixing liquids prevails in the zone of light hydrocarbons and oil displacement by gasses at the bed temperature predominates in the zone not affected by the thermal action.

Thus, almost all the known methods of acting on an oil bed in order to intensify oil extraction participate simultaneously when oil is being displaced by the action of intrabed combustion.

The material balance of the VG process with respect to the oil can be represented in the following form [39]:

$$I_p = I_{pe} + I_{cr} + I_{ptx},$$

where I_p = oil content of the bed before the beginning of the process; I_{pe} = amount of oil extracted as a result of the process; I_{cr} = amount of oil (coke residue) expended to maintain combustion; I_{ptx} = amount of hydrocarbon gas formed during the process.

The calculative formula for determining the oil yield factor for VG can be represented as

$$K_p = 1 - \frac{S_o + S_{tx}}{S_p},$$

where S_o = coke residue (as a percentage of the volume of the bed's pores),

$$S_o = \frac{g_{oct}\rho_{ck}}{\rho_p m};$$

S_{tx} = hydrocarbon gas content (percentage of the volume of the bed's pores), expressed as an equivalent amount of the original oil,

$$S_{tx} = S_o \frac{v_{oct} Q_t}{Q_p},$$

S_p = initial degree of oil saturation (percentage); g_{oct} = ratio of the mass of the coke residue to the mass of the rock in the bed; ρ_{ck} = density of the rock in the bed, kg/m^3; m = porosity of the rock in the bed, as a percentage; ρ_p = density of the original oil, kg/m^3; v_{oct} = specific flow rate of air per unit of coke residue mass, m^3/kg; Q_t, Q_p = respective heating capacities of the obtained gas and the original oil, kcal/m3 and kcal/kg.

In view of the fact that the combustion front does not completely encompass the entire volume of the oil-saturated bed, the oil yield factor for the entire bed (K_{cym}) depends on the envelopment factor A_v and the oil yield factor K for sections

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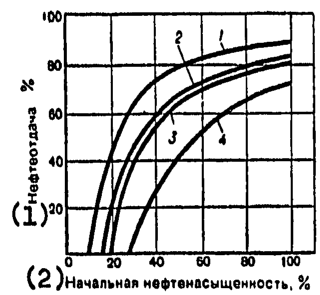

Figure 49. Dependence of oil yield factor on original degree of oil saturation when oil is displaced as a result of intrabed combustion (it is assumed that the amount of coke residue does not depend on the initial degree of oil saturation): 1. p_p = 800 kg/cm^2, m = 30 %; 2. p_p = 800 kg/cm^2, m = 20 %; 3. p_p = 1,000 kg/cm^2, m = 30 %; 4. p_p = 1,000 kg/cm^2, m = 20 %.
Key: 1. Oil yield, %
2. Initial degree of oil saturation, %

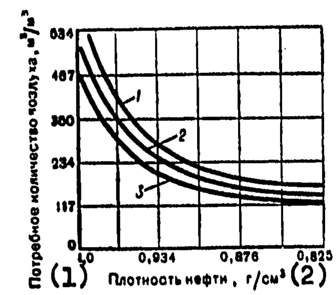

Figure 50. Dependence of specific air requirement on oil density (for an oxygen utilization factor of 100 percent and different degrees of porosity). Values of m, as a percentage: 1. 20; 2. 30; 3. 40.
Key: 1. Required amount of air, m^3/m^3
2. Oil density, g/cm^3

not enveloped by the combustion front:

$$K_{сум} = A_v K + \lambda (1 - A_v).$$

Figure 49 depicts the curves of the dependence of the oil yield factor K_p on the initial degree of oil saturation when VG is used [39].

The amount of coke residue that forms depends on the properties of the oil and the bed (tar content, porosity, degree of oil saturation, and so on), as well as on the process conditions (rate of movement, temperature of the combustion front). The dependence of the amount of this residue on the oil's density and viscosity, the carbon content and the hydrogen-carbon ratio (H/C), as derived for several groups of wells, is shown in the works of A.A. Abbasov.

The specific air requirement and the volume of air needed to burn out a unit volume of rock can be estimated approximately from the relationship shown in Figure 50.

Figure 51 shows the experimentally established [48] dependence of the oil yield factor on the viscosity of the oil.

As is obvious, the development of a bed with the help of VG is more effective than development with displacement of the oil by

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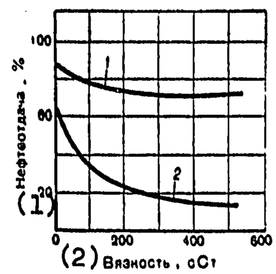

Figure 51. Dependence of oil yield factor on oil viscosity: 1. for oil displacement by the intrabed combustion process (initial degree of oil saturation 80 percent); 2. for oil displacement by water (90 percent water content).
Key: 1. Oil yield, %
2. Viscosity, cs

water. It is particularly advisable to use VG for deposits containing heavy oil. Bed development by the counterflow variant of VG can increase the oil yield up to 50 percent, while development by the direct-flow method can increase it by 70 percent or more [39]. In the process of extracting heavy oils, plugs form in the unheated part of the bed and injection of the oxidizing agent is carried out under high pressure. When the oil-bearing reservoirs lie at shallow depths, circuitous paths for the oxidant's movement can form when the pressure is increased.

The use of VG makes it possible to introduce into active industrial development deposits that have already been surveyed and that contain oil that is not being extracted by other widely used methods. In the USSR, the United States, the Czechoslovakian SSR, Japan, the FRG, and Venezuela, many installations for the use of intrabed combustion are being used successfully.

Selecting Deposits for Development With the Use of Intrabed Combustion

The effective realization of the intrabed combustion process depends largely on the correct choice of the oil deposit and a thorough substantiation of the features affecting the successful and economical use of this method.

In connection with this, it is necessary to take into consideration the depth of occurrence and the thickness of the beds, the size of the oil reserves, the degree of flooding of the beds, the oil's density and fractional composition, the formation pressure, the geological structure and reservoir properties of the beds, and the initial oil yield, which consideration makes it possible to develop a bed with the help of intrabed combustion more efficiently.

This method is recommended for use with deposits lying at depths of up to 1,500 m. The shallower the depth of occurrence, the lower the basic expenditures related to injecting the oxidizing agent into the bed.

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For intrabed combustion, the most favorable productive beds are those that are 3-25 m thick.

For a deposit to be developed with the help of VG, the degree of residual oil saturation must be at least 50-60 percent, while the initial degree of flooding must be no more than 40 percent.

For bed development by the VG method, the oil's viscosity and density can vary within rather broad limits: the viscosity must be at least 5 cp and the density must be no less than 0.82 g/cm^3.

On the basis of the data that are available, a deposit can be developed with the help of VG when the bed's porosity is 12-43 percent or more. Bed porosity has a substantial effect on the speed at which the combustion front moves and the pressure required for the oxidizing agent.

When an oil-bearing bed is being developed with the help of VG, it is advisable to use a dissolved gas regime, although this does not eliminate the possibility of using others, also.

Methods of Initiating the Intrabed Combustion Process

The initiation of combustion (ignition of the oil in the bed) during the implementation of VG is an important and critical operation.

As experience has shown, the amount of time required to create a combustion front in an oil-bearing bed differs. There are cases of rapid creation of the combustion front (several days), but this operation sometimes takes tens of days and longer.

Air, oxygen, and air enriched with oxygen can be used as the oxidizing agent during the initiation of combustion.

Bed oils are extremely variegated in chemical composition and physical properties, in view of which the characteristics of their oxidation also differ substantially.

According to experimental data, the ignition temperature of oil in a bed ranges from 150 to 400°C [31].

Spontaneous Ignition. Under the effect of oxygen injected into the bed from the surface, the bed oil oxidizes. This reaction frequently proceeds relatively rapidly. The oxidation reaction is accompanied by the liberation of heat and, if it takes place rapidly and is sufficient to balance the losses, the

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Table 28. Results of Research Performed by (Streyndzh)[1]

Мощность пласта, м (1)		Плотность нефти, г/см³ (4)	Пластовая температура, °C (5)	Давление нагнетаемого воздуха до зажигания, кгс/см² (6)	Количество нагнетаемого воздуха до зажигания, тыс. м³/сут (7)	Расчетное время для зажигания, сутки (8)
общая (2)	эффективная (3)					
11,28	10,67	0,9799	30,6	14,5	15,447	100
159,72	49,68	0,9692	51,7	66,8	28,314	17
116,73	71,62	0,9770	29,4	10,5 (120 сут) (9)	2,832	
				15,5 (30 сут)	33,980	150
152,40	67,06	0,9725	45,0	31,6 (54 сут)	56,630	62
				33,4 (8 сут)	84,950	
14,94	12,19	0,9854	60,0	83,3	5,154	13
23,16	15,55	0,9909	51,7	63,3	25,490	9
64,01	39,53	0,9593	35,0	28,1	9,061	24
60,65	27,43	0,9487	23,9	8,5	36,810	47

Key:
1. Bed thickness, m
2. Total
3. Effective
4. Oil density, g/cm³
5. Bed temperature, °C
6. Pressure of injected air before ignition, kg/cm²
7. Amount of air injected before ignition, m³/day
8. Theoretical time for ignition, days
9. ... days

oil-bearing bed can ignite without additional heat supplied from an outside source.

From Table 28 it is obvious that less time is required for the ignition of an oil-bearing bed with a higher bed temperature.

It is important to know the oxidation characteristics of bed oils in order to determine the economic feasibility of operations to promote the spontaneous ignition of the bed oils.

If the specific rate of the oxidation reaction is known, the time required for ignition of an oil-bearing bed can be calculated.

Streyndzh recommends the following formula:

$$\tau = \int_{t_f}^{t_i} \frac{C_f \rho_f e^{-\frac{E}{Rt}}}{Q f(p, S \ldots) A} dt,$$

where τ = time required for bed ignition; C_f = specific heat of the saturated, porous bed; ρ_f = density of the rock in the bed; Q = specific reaction heat of the reacting oxygen;

[1]Streyndzh, L.K., "Bed Ignition When Using Thermal Methods of Extracting Oil," INZHENER-NEFTYANIK (Petroleum Engineer), Nos 12 and 13, 1964, pp 12-14.

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$f(p,S)Ae^{-E/Rt}$ = specific reaction rate of the reacting oxygen; $f(p,S...)$ = functions of the oxygen pressure, the contact surface with the oil, and so on, as determined for each oil; A = = frequency factor; E = activation energy; R = universal gas constant; t = temperature; t_i = ignition temperature of the bed oil; t_f = bed temperature.

The values of C_f and ρ_f depend primarily on the bed's porosity and are practically identical in many cases. The reaction heat is also almost constant for normal hydrocarbon components that are found in bed oil.

The basic variable that is of practical interest and affects the spontaneous ignition of an oil-bearing bed is the specific reaction rate. Its value can be determined from core samples or a manmade specimen that contains oil sand and reproduces the bed conditions.

The time calculated by Streyndzh's formula is undoubtedly less than the time required for spontaneous ignition of an oil-bearing bed, because of the unavoidable losses of heat into the roof and floor of the bed under real conditions. However, a simplified calculation for adiabatic conditions has its advantages. If, for example, the bed ignition time is several hours or days, the possibility of spontaneous ignition should be investigated. However, if this time equals several months or years, there arises the necessity of using additional heat from an outside source.

In connection with this, it is necessary to take the following into consideration. If the actual bed temperature is low and the heat losses into the roof and floor exceed the initial ones in the oxidation process, spontaneous ignition of the bed oil does not take place (even when the calculated adiabatic time does not exceed several hours).

Most oil-bearing beds in which it is feasible to carry out heat treatments can be very thick. Their development with the use of intrabed combustion causes certain difficulties. Therefore, it is desirable that such productive beds contain easily oxidizable oil that is capable of spontaneous ignition when it reacts with oxygen. However, even this does not mean that the VG process can be developed favorably. In the opinion of several American investigators (Streyndzh, (Trantkhakh), (Shkhleyker)), conditions contributing to the effective manifestation of a gravitational regime can be created in thick productive beds.

During heating the oil's viscosity drops sharply, thanks to which the oil can flow to the bottom of the injection well because of the force of gravity.

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Ignition caused by oxidation does not begin right at the walls of the well's bottom. Despite the fact that the rate of oxidation in the bottom zone and the amount of heat liberated -- which depends on this rate -- are high (in connection with the presence of a high concentration of oxygen), the injected air moves the heat from the well bottom into the depths of the bed, so the oil will first ignite in a part of the bed that is somewhat removed from the ignition well's axis (for the direct-flow variant).

Thus, it is possible to develop the intrabed combustion process in two directions: toward the bottom of the well and into the depths of the bed. As a result, the temperature in the injection well's bottom zone can increase to a high value. As another result (particularly in the presence of free oil in the well), significant damage can occur even when thermally stable materials are used during the injection process.

In order to prevent such phenomena, different measures that insure (to a certain degree) the success of the work are used.

Initiation of Combustion by Introducing Heat. If it is intended to use VG to develop beds containing oil that is difficult to oxidize, so that spontaneous ignition is not guaranteed, heat is introduced into the bottom zone of the well in order to initiate combustion. In this case, various types of equipment (special deepset fuel burners, electric heating devices, chemical reagents, and so on) are first used to heat the ignition well's bottom zone to the bed oil's ignition temperature, after which the oxidizing agent is fed into this zone. In order to insure the presence of a stable and sufficiently powerful combustion front, both operations can be performed sequentially or simultaneously.

In order to create a combustion front in a bed, one of the many varieties of charcoal is sometimes used. In the Soviet Union, this method was first utilized in the 1930's [39].

Deepset (bottom) heating devices can be subdivided into fire (fuel) and electrical types.

Fire heaters, in turn, are categorized as diffusion (the fuel and oxidizer are fed into the combustion chamber separately) and mixing (the fuel mixture enters the combustion chamber in its prepared form).

The creation of the combustion front with electric heaters is more widely used. It is quite simple and convenient. The electric heaters used for this purpose operate for a long time

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Table 29. Results of Investigations of Artificial Bed Ignition

Месторождение (1)	(2) Мощность продуктивного пласта, м	(3) Плотность нефти, г/см³	(4) Давление, кгс/см²	(5) Подогреватель [4]	(6) Расход тепла, Гкал/м	(7) Номинальная мощность нагревателя	(8) Средняя скорость нагнетания воздуха при зажигании пласта, (м³/сут)/м
(9) Южная Оклахома [2]	6,0	0,933	9,14	Э (10)	0,32	45 кВт (11)	230
(9) Южная Оклахома [2]	5,2	0,944	10,55	Э	0,743	45 кВт	984
(12) Аллегжани, шт. Нью-Йорк [3]	10,4	0,811	—	Э	1,9	75 кВт	(Максимальная) (13)
(14) Гудвилхилл, шт. Пенсильвания [3]	18,3	0,949	52,73	Э	0,33	45 кВт	451
	6,1	0,925	25,31	Э	0,33	29 кВт	920
	5,5	0,938	6,0	Э	0,33	24 кВт	571
	6,1	0,969	15,12	Э	0,578	29 кВт	202
	—	1,001	21,8	Э	3,3 (Общее) (15)	24 кВт	11 960 (Общая) (15)
	24,4	0,949	58,36	Э	0,165	29 кВт	653
	18,3	0,949	64,7	О (25)	0,248	2,52 Гкал/сут (16)	708
	9,1	10,807	13,0	О	2,72	1,51 Гкал/сут	708
(17) Делавер-Чилдерс, шт. Оклахома	15,6	0,84—0,85	—	О	0,826	3,02 Гкал/сут	865
(18) Ниитсу, Япония	10,1	0,945	—	О	1,817	4,03 Гкал/сут	929
(19) Юго-Восточный Канзас	2,7	0,916	—	О	—	—	—
(20) Шанном, шт. Вайоминг	10,1	0,904	—	О	0,413	2,5 Гкал/сут	1122

[1] Стрейндж Л. К. Зажигание пласта при применении тепловых методов добычи нефти. — «Инженер-нефтяник», № 12 (21)
[2] Зажигание не достигнуто (22)
[3] Один вход через вырез в обсадной колонне (23)
[4] Э — электронагреватель, О — огневой нагреватель. (24)

Key:

1. Deposit
2. Thickness of productive bed, m
3. Oil density, g/cm³
4. Pressure, kg/cm²
5. Heater used
6. Heat expended, Gcal/m
7. Rated output of heater
8. Average rate of air injection during bed ignition, (m³/day)/m
9. Southern Oklahoma
14. (Gudvilkhill), Pennsylvania
15. Total
16. Gcal/day
17. Delaware-Childers, Oklahoma
18. (Niitsu), Japan
19. Southeastern Kansas
20. (Shannom), Wyoming
21. Streyndzh, L.K., "Bed Ignition When Using Thermal Methods of Extracting Oil," INZHENER-NEFTYANIK, No 12
22. Ignition not achieved

[Key continued on next page]

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Key to Table 29 (continued):
10. Electric
11. kw
12. Allegheny, New York
13. Maximal
23. One entry through opening in casing string
24. Э = electric heater; O = = fire heater
25. Fire

at the bottom of the well at a temperature above 700°C. Their power ranges from 10 to 74 kw. In order to insure the best heat transmission, the space between the electric heater and the well's walls (and the joint around the ignition well) should be filled with a material with good heat conductivity, such as metal particles.

If difficulties in initiating combustion arise because of clogging of the bed's pores with heavy oil, it has been suggested that the heater be turned off periodically while the oxidizing agent continues to be injected. The results of field experiments show that the permeability of an oil-bearing bed increases after a series of such operations. The operations are repeated until combustion can be maintained by oxidant injection alone.

It is sometimes possible to achieve stable combustion only after several cycles.

An analysis of the work done on creating a combustion front by introducing heat shows that oxidant consumption rates per unit of bed thickness are 22-200 (m^3/day)/m (Table 29).

Heat consumption for the heating of 1 m of oil-bearing bed thickness varies from 0.25 to 2.72 Gcal. The amount depends on the heating time and the bed oil's ignition temperature. In connection with this, the heat expended to generate the electricity used to compress the air injected into the bed was not taken into consideration.

The enumerated methods of creating a combustion front do not exhaust all the possibilities. There are a number of patents and author's proposals, the implementation of which might be useful in the realization of this process.

Formation of a Combustion Front in a Bed. The energy expended to create a combustion front can be quite significant. Therefore, it is important to determine the moment of oil ignition in the bed as early as possible.

The time in which the bed can ignite and the combustion front be created depends on the bed's characteristics, the bed oil's physicochemical properties, the method of ignition, the design

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THERMAL METHODS OF DEVELOPING PETROLEUM DEPOSITS

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and power of the submerged heater, the layout of the ignition well's bottom, and other factors.

The formation of the combustion front during spontaneous ignition of the bed oil can be judged by the change in temperature. In order to accomplish this, a thermocouple or any other thermally sensitive device is installed in the ignition (injection) well. In order to obtain a more precise indicator, oxidant (air) injection into the bed is halted at the time of the measurement in order to reduce the cooling of the thermally sensitive device.

The moment of appearance of the combustion front can be determined by analyzing gasses taken from the operating wells. In most cases gas breaks through into the operating wells and is detectable shortly after the beginning of oxidant injection into the bed. The vented gasses are initially characerized by a high hydrocarbon content, after which carbon dioxide, carbon monoxide and oxygen begin to appear. A reduction in the gas's oxygen content usually signifies formation of the combustion front.

For bed oils that react well with the oxygen in air, spontaneous ignition can occur so early that there will generally be no oxygen in the gas that is extracted or the gas's oxygen content will be extremely insignificant.

When air is used as the oxidizing agent, the CO_2 and CO concentrations in the vented gasses are 8-16 and 1-4 percent, respectively.

However, it should be taken into consideration that CO_2 dissolves easily in oil and water and occasionally is not detected in the vented gasses for some time. Carbon monoxide is less soluble and, although its concentration is lower, it is by the appearance of this gas in the vented gasses that the moment of bed ignition can be best determined.

When a combustion front is being created with the help of heaters, the moment of the appearance of combustion can also be determined by temperature measurements and by data from an analysis of the vented gasses.

Whether the combustion front is created by spontaneous ignition of the oil or combustion is initiated by the introduction of heat, the composition of the gasses is identical. However, the vented gasses may contain more oxygen before the beginning of combustion front formation in the case of the latter method.

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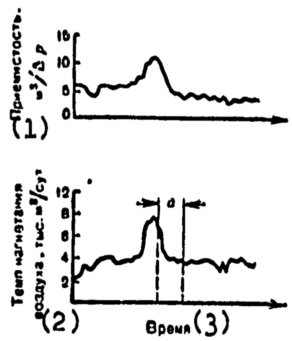

Figure 52. Reduction in well receptivity with respect to air at the moment of oil ignition.
Key: 1. Response, $m^3/\Delta p$
2. Rate of air injection, 1,000 m3/day
3. Time

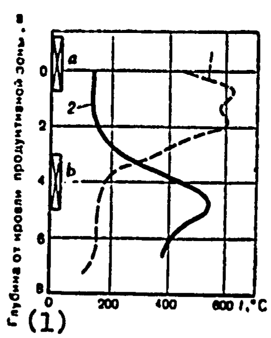

Figure 53. Thermograms taken during ignition of bed oil with the help of a deepset electric heater.
Key: 1. Depth from roof of productive zone, m

The creation of the combustion front is sometimes established according to the nature of the change in the well's receptivity with respect to air, with the help of so-called "liquid" blocking [48].

Figure 52 shows the changes in the rate of air injection and well receptivity during the period of combustion front formation in an oil-bearing bed. As field experiments have shown, when the oil ignites, at first the rate of oil displacement from the injection well's bottom zone and the well's receptivity with respect to air increase rapidly. Shortly thereafter, however, the receptivity drops sharply. This can be explained by the creation of a "liquid barrier" ahead of the flow that lowers the phase permeability for air in the zone ahead of the combustion front.

As the combustion front is further displaced, the bed's receptivity with respect to air can again increase or can be stabilized. The time when the receptivity with respect to air reaches its maximum and then drops abruptly indicates the ignition of the oil in the bed.

The moment of oil ignition can also be determined from thermal logging diagrams. Figure 53 shows curves registered during thermal logging [57]. Curve 1 corresponds to the heater's position (a). It is obvious that combustion began in the upper part of the productive zone (about 2.4 m). Only a small quantity of air (or, generally, none at all) reached a depth of more than 3.4 m below the roof of the bed.

After the monitoring work to determine the clearing of liquid from the bottom zone was performed, repeated thermal logging

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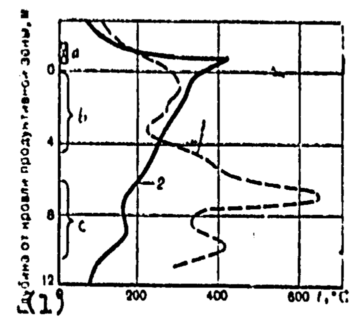

Figure 54. Thermograms taken with the help of deepset fire (gas) heaters during bed oil ignition.
Key: 1. Depth from roof of productive zone, m

(curve 2) was conducted with the heater is position b. In this case, it is obvious that ignition occurred successfully.

Figure 54 shows temperature curves registered during the ignition of a bed by gas burners. The control bed oil ignition temperature is 250°C. Active combustion is obviously taking place at a depth of 6.7 m below the bed's roof. However, it is fully possible that the oil burned only in the range of the well. The control temperature in curve 2, which was recorded several hours after the first measurement (curve 1), shows a residual peak that confirms intrabed combustion, despite the fact that the well had cooled in the interval between the measurements.

Thus, temperature measurements and monitoring of the analyses of the extracted combustion products (and their correct interpretation) are a reliable means for confirming oil ignition in a bed.

Wet Combustion

The wet intrabed combustion method is receiving ever wider recognition in worldwide practice. Its value is that it lowers the air-to-oil ratio substantially and improves the technical and economic indicators of the process.

The difference between dry and wet intrabed combustion is as follows. When water is added to the injected air, the gas flow's thermal capacity is increased considerably. Injected dry air cannot remove heat from hot, burned-out rock at the same rate at which the combustion front heats the rock, whereas the addition of water increases the injected gas-and-liquid mixture's capability to remove heat in the burned-out zone. The wet VG process is accompanied by the formation of an extensive zone of saturated steam ahead of the combustion front that improves the oil displacement conditions. When the combustion front is in the same position (for both dry and wet VG), more oil is displaced during wet VG because the zone containing steam and hot water is in motion far ahead of the combustion front. In this case there is also a drop in the fuel

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concentration, which leads to a reduction in the specific air consumption.

An increase in the water-to-air ratio of from at least 0.002 m^3/m^3 to 0.01 m^3/m^3 results in a lowering of the combustion front's temperature and the VG process is then called superwet.

Wet and superwet VG contribute to an improvement in the utilization of the heat generated in the bed. Heat is transferred into the zone ahead of the combustion front. In the limiting case, practically all the heat liberated as the result of the combustion is regenerated ahead of the combustion front.

The presence of a rather large fringe of steam ahead of the combustion front makes it possible to halt the combustion process considerably earlier than during dry combustion, and this leads to a reduction in air consumption by a factor of 2-3.

Research into wet VG shows its great possibilities for the development of oil-bearing deposits.

Wet and superwet VG are realized by either simultaneously or alternately injecting water and the oxidizing agent (air) in a certain ratio.

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CHAPTER 4. EXPERIMENTAL INDUSTRIAL PROJECTS FOR THE INTRODUCTION OF THE INTRABED COMBUSTION METHOD OF DEVELOPING DEPOSITS

[Text] The idea of creating a method for developing oil deposits using intrabed combustion belongs to Soviet science. In 1932-1934, A.B. Sheynman, K.K. Dubrovay, S.L. Zaks, N.A. Sorokin, and M.M. Charygin, who were all scientific workers at GINI, did extensive laboratory research on the use of intrabed combustion. The first experiments in the world on the creation of VG were conducted in the Soviet Union, in the Shirvanskoye field in Krasnodarskiy Kray [39].

Experiments were performed until 1941, when they were interrupted by the war. Beginning in 1964, projects for the use of this method to develop develops on industrial scales were again begun at enterprises in Krasnodarskiy Kray. A plan for an experimental industrial installation was drawn up through the joint efforts of the Krasnodarsk branch of VNIIneft' (later known as KrasnodarNIPIneft'), IGiRGI [Institute of Geology and Development of Mineral Fuels], Krasnodarnefteproyekt, and the Khadyzhenneft' NGDU [Oil and Gas Production Administration], and an experiment in the use of intrabed combustion was successfully carried out in the USSR beginning in late 1966.

In 1967, experimental work was begun in Lens 4 of the Sarmatian horizon of the Zybza heavy oil deposit. This was proceded by preliminary planning work performed by the three [sic] institutes named above.

The Pavlova Gora and Zybza oil deposits, in which the work was begun, differ sharply in both physical and geological field characteristics.

The Pavlova Gora deposit is more suitable for the use of intrabed combustion than the Zybza heavy oil deposit.

The former consists of an areally persistent, granular, highly oil-saturated bed, whereas the latter has interlayers of clays,

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aleurites, and dolomite, clay and coarse scree breccia. The oil reservoir consists of oil-saturated rocks or voids formed by the breccia, from which the oil was displaced by water.

By working with deposits having different characteristics, it is possible to achieve a considerably fuller understanding of all the factors affecting the effectiveness of the development of oil-bearing beds with the intrabed combustion method, and this also facilitates the accumulation of practical experience for the further expansion of the use of the thermal method of extracting oil.

Results of the Use of Intrabed Combustion in a Homogeneous Bed in the Pavlova Gora Oil Field

A Brief Industrial Geological Description of the Oil Pool in the Western Embayment of Maykopskiy Horizon 1 in the Pavlova Gora Field

The Pavlova Gora oil-bearing area lies 3 km northwest of the settlement of Neftegorsk.

The presence of oil in horizon 1 of the Pavlova Gora field's western embayment was established as far back as 1938, by logging data. The horizon was not tested until 1957, and as a result of the testing an oil flow of up to 5.4 tons/day was obtained.

There is also oil in horizon 1 of the adjacent eastern embayment of Pavlova Gora, which is connected to the western one by a neck of rock. In the eastern embayment, the rock deposits forming the horizon have been eroded, and in the highest part the productive packet of deposits reaches the diurnal surface.

Inside the Pavlova Gora field, Maykopskiy horizon 1 consists of four parcels of sand or sandstone that are separated by clay interlayers.

The western embayment is confined to monoclines with dip angles of about 11° toward the northeast. On the northeast it is held back by contour water. The length of the pool along the strike is about 1,000 m in the western embayment, while its average width is 850 m (Figure 79). The depth of occurrence of the bed in the area of the wells varies from 91 m in the most elevated part to 275 m near the edge of the oil-bearing area. The effective thickness of the oil-saturated second parcel of horizon 1, which is the site where deposit development with the intrabed combustion method was practiced, increases from the point where it tapers out to 10 m in the area of injection well 804.

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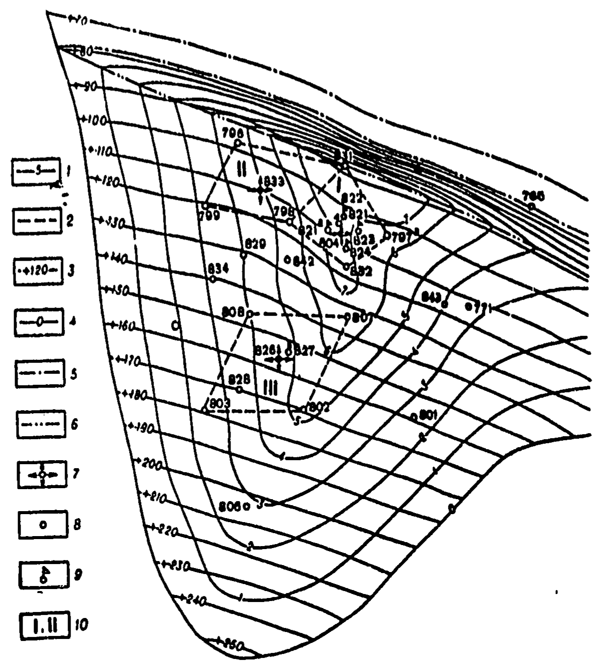

Figure 79. Map of development of Maykopskiy horizon 1 in the western embayment of the Pavlova Gora field: 1. isopachs; 2. boundaries of experimental sections; 3. isohypses along the roof of Maykopskiy horizon 1; 4. petering-out line of reservoirs in Maykopskiy horizon 1; 5. original external oil pool outline; 6. original internal oil pool outline; 7. injection wells; 8. operating wells; 9. observation wells; 10. experimental sections.

Drilling was conducted in the western embayment in a triangular network, with a distance of 200 m between wells. By the middle of 1960, 12 wells had been drilled. According to the technological plan, the existing wells were to be supplemented with additional ones.

The horizon's productive band was studied in detail with the help of core samples taken during the drilling of six wells in the first experimental section and two wells in the second one, using an oil-based flushing solution. Core sample extraction was 60 percent. The main part of the samples consisted of slightly cemented sands and aleurites. Dense sandstones and clays were encountered in the form of thin interlayers (up to several centimeters thick).

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Table 31.

Номер скважины (1)	Эффективная мощность, м (2)	Пористость, % (3)	Проницаемость, мД (4)	Нефтенасыщенность, % (5)
804	7,7	25,0	1036	68,1
821	5,0	24,9	1990	75,8
821а	7,0	24,2	1265	71,0
823	5,9	25,0	828	70,0
831	4,0	27,5	321	69,4
832	7,5	24,0	956	74,4
826	3,5	21,7	288	—
827	4,3	24,1	530	—

Table 32.

Опытный участок (6)	Среднее значение параметра (7)			
	пористость, % (3)	проницаемость, мД (4)	нефтенасыщенность, % (5)	эффективная мощность, м (2)
Первый (район скв. 804) (8). . . .	25,0	1100	71	7,0
Второй (район скв. 826) (9). . . .	22,9	410	—	4,0

Key to Tables 31 and 32:
1. Well number
2. Effective thickness, m
3. Porosity, %
4. Permeability, md
5. Oil saturation, %
6. Experimental section
7. Average value of parameters
8. First (in area of well 804)
9. Second (in area of well 826)

The results of a determination of the physical properties and degree of water saturation of the core samples are shown as weighted average values for each well in Table 31.

The average values of the bed's parameters are shown for the first two sections in Table 32.

As far as the state of affairs in 1966 was concerned, the oil saturation of horizon 1 averaged 71 percent for the bed as a whole. The original formation pressure in the deposit, as reduced to the water-oil contact, was 15 kg/cm^2. The current formation pressure ranged from 2 to 12 kg/cm^2.

Table 33 gives a description of the oil, data on the deposit and several parameters relating to the technology of the process.

Exploitation of the deposit was begun in October 1957, with an oil flow rate of 6.5 tons/day. The maximum average daily oil flow rate for the deposit was 21 tons. The oil flow rate then

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Table 33.

Наименование (1)	Первый участок (2)	Второй участок (3)
Площадь, га (4)	1,545	1,5
Средняя глубина залегания пласта, м (5)	247	225
Эффективная мощность пласта, м (6)	7	4
Пористость, % (7)	25,0	22,9
Проницаемость, мД (8)	1100	410
Нефтенасыщенность, % (9)	71	71
Пластовая температура, °C (10)	21	21
Плотность нефти, г/см³ (11)	0,945	0,945
Вязкость нефти в пластовых условиях, сП (12)	173	173
Содержание акцизных смол, % (13)	36	36
Атомное отношение (H/C) (14)	1,587	1,587
Температура начала кипения, °C (15)	90—102	90—102
Коксовый остаток (топливо) (16)	28,4	28,4
Удельный расход воздуха на горение, м³/м³ (17)	350	350
Коксуемость нефти, % (18)	4,5—5,3	4,5—5,3

Key:
1. Parameter
2. First section
3. Second section
4. Area, ha
5. Average depth of occurrence of bed, m
6. Effective thickness of bed, m
7. Porosity, %
8. Permeability, md
9. Oil saturation, %
10. Formation temperature, °C
11. Oil density, g/cm3
12. Oil viscosity under bed conditions, cp
13. Asphalt tar content, %
14. Atomic ratio (H/C)
15. Temperature at onset of boiling, °C
16. Coke residue (fuel)
17. Specific air consumption rate for combustion, m3/m3
18. Coking capacity of oil, %

dropped continually and by the end of 1964 had stabilized at a level of 5 tons/day, with 13 extraction wells in operation.

In May 1961, water was injected into the bed in order to maintain the formation pressure. However, the addition of water was soon halted because it broke through into the operating wells. After the water injection was stopped, pure oil gradually began to be obtained from the flooded wells.

From the curve of the actual decrease in the oil yield from the western embayment (before the initiation of intrabed combustion), it was calculated that the profitability limit (an oil yield of 50 kg/day per well) for well operation without the use of intensification methods would be reached in 1977, when the total amount of oil extracted from the western embayment would be 30,500 tons. This means that the bed's final oil yield, after being fully depleted, would have been 11.7 percent.

Equipment Used in Intrabed Combustion and the Technology of This Process in the Pavlova Gora Field

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The oil-bearing bed in the heavy oil deposit of the Pavlova Gora field has been developed by the "dry" VG method in two experimental sections (see Figure 79), using an inverted five-point layout with a single injection well in the centers of the systems, from which the intrabed combustion process is carried out by the direct-flow variant. Observation wells were drilled between the injection and operating wells, for the purpose of intermediate monitoring. At the present time, a technological plan for conducting wet combustion is being drawn up. The location of the wells in the third section can be seen in Figure 79.

The installation consists of the following basic assemblies:
1) a compressor station, which provides a supply of air and gas from three 8GK gas-motor compressors;
2) main gas and air lines from the compressor station to the distribution unit in the experimental section in the field;
3) a compressed air and fuel gas distribution unit for the wells in the experimental section and a unit for collecting the waste gasses for direction to the burning point;
4) monitoring and measuring instruments and automation equipment (instruments for visual monitoring, the recording of results, and the controlling of processes during the experimental work);
5) injection, operating and observation wells;
6) a group installation that includes one measuring and two working ladders with monitoring and measuring devices and automated equipment;
7) a building housing a chemical laboratory.

The air and gas distribution in the experimental industrial section is shown in Figure 80.

During the experimental work, the compressor station was reorganized, with the 2SG-50 compressors being replaced by 8GK compressors.

The proposed technological plan provides for the following operations when developing an oil-bearing bed with the help of intrabed combustion:
1) the supplying of fuel gas and air to the bottomset fire heater, which is installed in the injection well during the period of the oil-bearing bed's ignition;
2) the injection of an oxidizing agent (air) into the oil-bearing bed through an injection well for the purpose of maintaining and moving the combustion front away from the injection well toward the operating ones;
3) halting the supplying of the oxidizing agent (air) in the interpipe space of the operating wells (when necessary), for the purpose of injecting it in a direction opposite to that of

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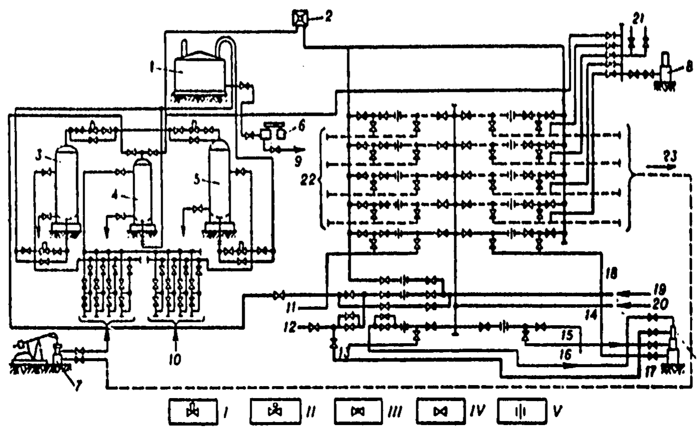

Figure 80. Collection and separation of output extracted during intrabed combustion in the Pavlova Gora field: 1. reservoir; 2. waste gas burning point; 3. working ladder in first experimental section; 4. measuring ladder; 5. working ladder in second experimental section; 6. pumping station; 7. operating wells; 8. observation wells; 9. supply of oil to industrial collection point; 10. output from operating wells in second experimental section; 11. technological air into the second experimental section; 12. gas for combustion in deep heater in the second experimental section; 13. air for cooling deep heater; 14. technological air to maintain combustion in the bed in the second experimental section; 15. air for cooling deep heater; 16. air for combustion in deep heater; 17. gas for combustion in deep heater in the first experimental section; 18. technological air to maintain combustion in the bed in the first experimental section; 19. gas from compressor station; 20. air from the compressor station; 21. sampling of combustion waste gasses for analysis; 22. to space beyond pipes in operating wells in the second experimental section; 23. to space beyond pipes in operating wells in the first experimental section; I-IV. valves; V. flow meters.

the moving combustion front in order to intensify the oxidation process;

4) utilization of waste gasses from the operating wells by burning them or injecting them into the bed;

5) supplying air into the system of monitoring and measuring instruments and the automation equipment;

6) forcing oil out of the traps and into the group reservoir with the help of gas.

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The technological plan also makes it possible to carry out the following operations at the same time:
1) feed the oil extracted from the operating wells into a group installation and separate the gas and water from it;
2) remove waste combustion gasses from the interpipe space of the operating and observation wells;
3) take periodic gas samples from the interpipe space of the observation and operating wells and from the measuring ladder, and send them to automatic gas analyzers in order to determine the content of O_2, CO, CO_2, and CH_4;
4) record the fuel gas and air flow rates during the period of the oil-bearing bed's ignition, as well as the consumption rate of oxidizing agent (air) to maintain the intrabed combustion, the consumption of fuel gas to burn up the hydrocarbons and carbon monoxide in the waste gasses, and the consumption of the air needed to cool the housing of the bottomset fire heater in the injection well.

Structure of the Operating, Injection and Observation Wells. An engineering column that had been cemented to the well mouth was lowered into these wells. The productive bed was revealed with a flushing solution dissolved in an oil base.

In order to protect the engineering column from the effect of the high temperatures, its based was covered with a tail piece of heat-resistant perforated pipe 11-26 m long. There were 100 preliminarily drilled 3-mm holes in every meter of the pipe. An asbestos-graphite gasket was installed between the engineering column and the tail piece.

The injection wells were cased with a string 219-273 mm in diameter, while the diameter of the string in the operating and observation wells was 146-219 mm. The tail piece was somewhat smaller, being 114-146 mm in diameter.

As data were accumulated on the conduct of intrabed combustion, all the newly drilled wells were driven into the productive bed and cased with a 146-mm engineering column cemented to the well mouth. This column was then perforated opposite the productive bed.

From the beginning of operation of the wells there was intensive erosion of sand from the bed, even at low (1-1.5 tons/day) oil removal rates. During the intrabed combustion process, intensive destruction of the wells' bottom zones and the formation of sand plugs were observed. The operation of the deep pumps was made more difficult, and the wells had to be repaired frequently.

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Bottomset gravel filters, which were metal filters with a fine mesh, were used during the experimental work in order to insure stable operation and to combat sand erosion. However, this did not yield the desired result. In 1972, work was begun to reinforce the loose sand by the coking method, which made it possible to prevent the destruction of the wells' bottom zones in the bed.

Experimental Industrial Work and Research Done in the Pavlova Gora Oil Field

The program of experimental industrial projects stipulated that the following work would be done:
1) development of a method for creating a combustion front and the technology for igniting a bed, as well as the testing of deepset heating equipment and instruments;
2) the gathering of data on the effectiveness of intrabed combustion;
3) the checking of results of laboratory experiments;
4) the gathering of data for preliminary technical and economic calculations.

The program consisted of four stages:
1. Investigation of the functioning of the operating wells in the deposit before the experimental injection of air into the bed.
2. A study of the hydrodynamic conditions present during the injection of air into the bed and their effect on the exploitation of the deposit.
3. A study of means for igniting the oil-bearing bed and the implementation of operations to create and move the combustion front.
4. A study of direct-flow dry combustion over an extended period of time.

Performance of the Operating Wells Prior to Air Injection. This stage was conducted for the purpose of obtaining data under the operating conditions common to the deposit, as well as to test the output collection, separation and measurement systems that had been constructed. The data obtained were the starting point for evaluating the operational effectiveness of the thermal process.

Special attention was given to the functioning of the wells in the experimental section. All the assemblies in the installation were adjusted at the same time that the collection and processing of the primary data were being organized. Measurements were taken of the obtained output (oil, gasses and water), the dynamic and static levels, the characteristics of the oil, gasses and water, formation temperatures, and pressure.

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Study of the Hydrodynamic Conditions During the Experimental Injection of Air Into the Bed. The following were determined in connection with the experimental injection of air into the bed through an injection well: receptivity of the well, distribution of the air flows among the operating wells, and the bed oil's capability for spontaneous ignition without extraneous heat in the bottom zone.

The oxidation processes were judged by the change in the composition of the gas output (reduction of the oxygen content and the appearance of carbon dioxide and carbon monoxide) and by the temperature changes in the injection, observation and operating wells.

Along with the measurements that were taken in this stage, the injection regime was monitored (the flow rate, pressure and temperature of the injected air were determined) and the nature of the oil inflow in the injection well was established. At first, up to 12,000 m^3/day of gas was injected; this figure was later increased to 27,000 m^3/day.

Creation of an Intrabed Combustion Front in the Two Experimental Sections in the Deposit. In accordance with the program, the following equipment and devices for creating an intrabed combustion front were tested:
1) deepset fire heaters operating on gaseous fuel;
2) deepset electric heaters;
3) coal packets.

In order to work out a method for creating a combustion front, it was decided to use IGiRGI's furnace equipment and Ishimbayneft' [Ishimbay Petroleum Industry Trust] NPU's [Oil Field Administration] thermal injector, both of which operate on gas fuel. A ground-level test stand and a test well were used in connection with this. The heating device was lowered in a column 146 mm in diameter. The waste gasses were drawn to the surface through the space beyond the pipe. Counterpressure at the outlet was supplied by an 04 MSTM-410 pressure regulator.

Testing of Ishimbayneft' NPU's thermal injector in the test well, at different pressures, showed that it could not be used to create a combustion front, since it would not function for long periods of time at pressures above 25 kg/cm^2. Testing of IGiRGI's furnace equipment was not performed in view of the danger of its exploding, which is related to the supplying of a prepared gas and air mixture to the well mouth and the heater and because of the lack of reliability of its electric igniter.

A new design for a heating device operating on gas fuel was developed at KF VNII [Krasnodarsk Branch of the All-Union

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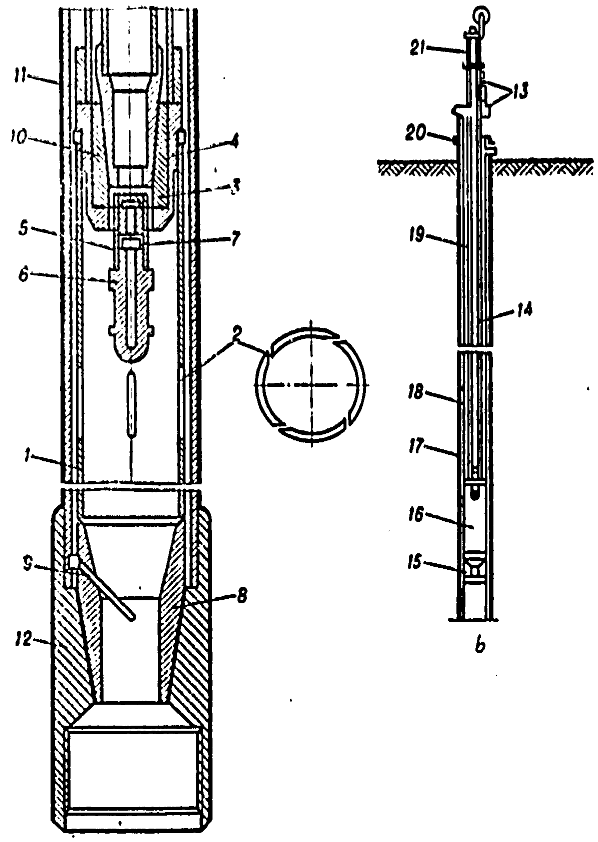

Figure 81. Well-bottom gas burner: a. burner; b. installation of burner in well; 1. housing; 2. tangential slots; 3. distributor of air and gas for combustion; 4. socket; 5. reducer; 6. nozzle; 7. mantle; 8. conical stem; 9. housing for thermocouple; 10. cone-shaped tip of 38-mm pipe; 11. column for lowering heating device; 12. conical socket for holding heating device; 13. gasket; 14. 63-mm compression and pumping pipe; 15. seating socket; 16. gas burner; 17. 168-mm compression and pumping pipe; 18. 102-mm compression and pumping pipe; 19. 38-mm compression and pumping pipe; 20. well-mouth equipment; 21. lubricator.

Scientific Research Institute of Petroleum and Gas] [31]. This heating device is shown in Figure 81. Air and gas are fed into the combustion chamber separately. The secondary air, which

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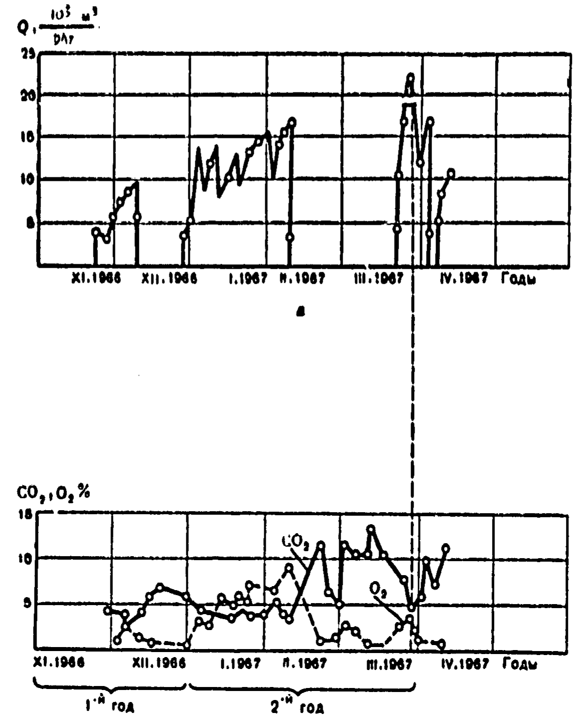

Figure 82. Indicators characterizing the creation of intrabed combustion in the first experimental section at Pavlova Gora: a. air injection into well 804; b. CO_2 and O_2 content of gas extracted from well 798.

enters the combustion chamber tangentially, stabilizes the flame and cools the housing. The tangential supplying of air makes it possible to control the temperature of the waste gasses and keep it between 200 and 1,000°C. All of the heater's parts were made from heat-resistant 1Kh18N9T steel. A rocket igniter with a gas cylinder was used to start the heater. The heater's rated capacity was 150 kw. Operation of the heater in the test well, for 23 hours at pressures of 16 and 22.5 kg/cm^2, showed that as the pressure increases, so do the requirements for the heat resistance of the combustion chamber's parts. However, the combustion process proceeded smoothly and no complications arose when the heater was started and controlled by changing the gas and secondary air flow rates.

In accordance with the planned program, experimental air injection into the bed was begun through injection well 804, in the

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first experimental section, on 22 November 1966. The experimental air injection was carried out in three stages, between the latter two of which the duration of the cessation was different (Figure 82).

Analyses of the gas showed that the oxidation process was in progress several days after the beginning of air injection into the bed. By the end of the first period of air injection (25 November to 10 December 1966), the O_2 content in the gas from well 798 (which reacted most actively to the injection of air) was 3.2 percent. In the period after injection was halted (10-29 December 1966), the O_2 content of the gas from this well dropped to 0.3 percent, while the CO_2 content rose to 6-7 percent. During the first stage, 103,600 m^3 of air was injected.

With the resumption of air injection, the CO_2 content of the gas from well 798 gradually decreased to 4 percent, while the O_2 content rose to 8.5 percent. During the second stage (29 December 1966 to 10 February 1967), 374,000 m^3 of air was injected.

After injection was halted for the second time (10 February to 22 March 1967), the CO_2 content of the gas from well 798 rose to 13.6 percent and the O_2 content dropped to 0.2 percent. During this period the temperature in the observation wells increased from 21 to 38°C. Such a change in the gas composition and temperature indicated that oil oxidation was taking place in the bed.

The injection of air was resumed on 23 March 1967. The well's receptivity increased from 16,000 to 28,000 m^3/day in the period 23-29 March 1967, as the pressure at the well's mouth was raised from 25 to 35 kg/cm^2. Further, despite raising the pressure to 36 kg/cm^2, the well's receptivity dropped to 11,500 m^3/day. With the resumption of air injection, the O_2 content of the gas from well 798 decreased from 3.8 percent, and by 7 April did not exceed 0.1 percent. During this period the CO_2 content rose from 5 to 10 percent. After 31 March 1967, the O_2 content of the gas extracted from the wells (798, 831, 807, 821a, 823, 821, 832, 771) did not exceed 1-2 percent, the CO_2 content did not drop below 8-14 percent, and the amount of CO in the gas from the observation wells was 1-2 percent. These data are indicative of the formation of an intrabed combustion front.

The creation of a combustion front in the area of well 804 was confirmed by temperature measurements in well 821, the bottom of which was at a distance of 3.8 m from the bottom of well 804, and be data from the thermocouples in well 804, which is 14.5 m

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above the roof of the bed. A temperature of more than 218°C was recorded at the bottom of well 821 on 12 April 1967. Lead that was lowered to the bottom of this well on 15 May 1967 promptly melted, which indicated a temperature of more than 327°C.

The creation of a combustion front was confirmed by the drop in injection well 804's receptivity after 31 March 1967.

An analysis of the available data shows that 29 March 1967 can be regarded as the date of creation of the combustion front in the first experimental section.

In the second experimental section (in well 826), the combustion front was created with the help of the heating device developed by KF VNII.

In connection with the fact that there were shutdowns at the compressor station, it became necessary to stop operating the heater. It functioned for three periods before the creation of the combustion front. In the first period (27 December 1968), when the well-mouth pressure was 29 kg/cm^2, 434,000 kcal of heat was introduced into the bed in 4.5 hrs. In the second period (8 January 1968), which lasted for 3 hrs, 128,000 kcal of heat was introduced. During these periods, in the well (327) closest to the injection well, there was a drop in the O_2 content from 10 to 0.2 percent and an increase in the CO_2 content from 5 to 16 percent, whereas in well 803 the O_2 content remained high (up to 10 percent) and the CO_2 level was 2-8 percent.

The third time (7 February 1969), the heater operated for 54 hrs in well 826, until the combustion front formed. The heater's operating regime, at a pressure of about 30 kg/cm^2 for a period of 24 hrs (8-9 February 1969), are shown in Figure 83. The temperature of the waste gasses from the heater ranged from 510 to 840°C. The bed received 6 million kcal of heat.

By the end of the heating of well 826's bottom zone, there was almost no oxygen in the waste gasses from all the operating and observation wells. The date of combustion front formation is considered to be 9 February 1969.

After the combustion front had moved away from the bottom of the injection well, its receptivity continued to increase for some time.

Development of the Intrabed Combustion Process at Pavlova Gora (Figure 83). The following questions were included in the study of the intrabed combustion process: monitoring the advance

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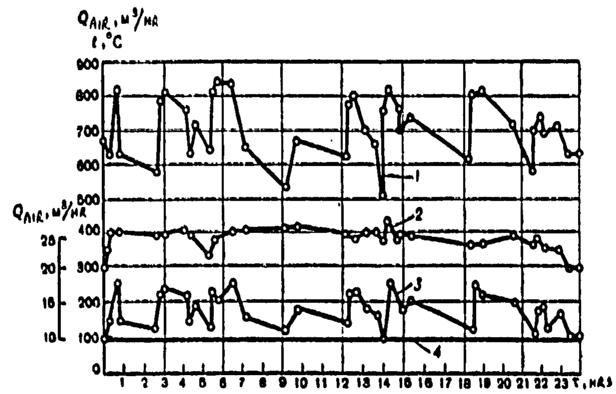

Figure 83. Description of the performance of the bottomset gas burner in well 826 in the Pavlova Gora field (8-9 February 1969): 1. temperature of waste gasses; 2. flow rate of air for cooling; 3. flow rate of gas for combustion; 4. flow rate of air for combustion.

of the combustion front and determining the zone of bed envelopment by combustion; controlling the process; studying the effect of the process on liquid and gas extraction; studying the factors affecting the performance of the equipment, and others.

After the combustion front was created, there was a systematic analysis of the O_2, CO_2 and CO contents in the extracted output.

The amounts of O_2 and CO_2 in the extracted gas were determined by periodically sampling the gas from the well and analyzing it with the help of an ORS portable gas analyzer.

The monitoring of the gas's composition revealed that reliable results are obtained with gas from the operating wells.

The continuous extraction of output from these wells insured that the gas samples reflected the bed conditions at the moment they were taken. When gas samples are taken only periodically from nonoperational observation wells, it is possible to obtain distorted data on the composition of the gas. As is well known, CO_2 dissolves easily in oil. After observation wells have stood idle and a depression has been created at their bottom, the gas filtering through the bed can be supplemented by part of the CO_2 liberated from the oil. Because of this, a CO_2 content of up to 25 percent or higher has been seen in gas samples from observation wells, whereas during combustion the CO_2 content of the waste gasses cannot be greater than 21 percent.

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The bed temperature in the observation wells was monitored along the profile of the bed (every 1-1.5 m) with the help of thermocouples, with the results being recorded by the monitoring and measuring instrument complex. The temperature in the operating wells was measured with maximum mercury thermometers during the underground repair period. The bed oil's properties were determined from recombined samples.

The data gathered since 1967 on the O_2, CO_2 and CO contents of the extracted gas have been indicative of effective progress of the intrabed combustion process in the first experimental section; the same has been true for the second section since February 1969. Basically, the O_2 content of the gas from the wells varies from zero to fractions of a percent. The CO_2 content fluctuates from 12 to 17 percent, and during the first months of the process, the CO content of gas from observation wells in the first section was 1-2 percent, after which it dropped to 1 percent and even lower (data on the CO content are available only up to November 1968).

A variation from the general pattern of the gas's composition was seen in separate periods for wells 798, 821a, 821, 803, 802, 823, and 771 only. There was an increase in the O_2 content and a decrease in the CO_2 content, which was related to a breakthrough into the wells of the air being injected into the bed when the combustion front passed through the bottom of the observation wells and pure air reached them. In order to eliminate the breakthrough of air into the operating wells, their yield rates were limited or extraction was temporarily halted. After some time had passed, they were put back into normal operation.

From the data on the bed temperature in the observation wells (Figure 84) it is possible to conclude that in the first experimental section, the combustion front was clearly registered in only two wells (well 821 on 15 April 1967 and well 821a in September 1968). At the beginning of March 1970, the approach of the combustion front was registered in well 827 in the second experimental section.

Examining the temperature distribution along the bed's profile in the observation wells (Figure 85), we see that its maximum value is reached in the central part of the bed and that it drops abruptly toward the bed's roof and floor. This is explained by the losses of heat through the bed's roof and floor when the combustion front moves through it. In wells 821, 822 and 824 we also note a tendency toward temporal displacement of the temperature maximum toward the roof of the bed, which is related to gravitational separation of the oil and water as they filter through the bed.

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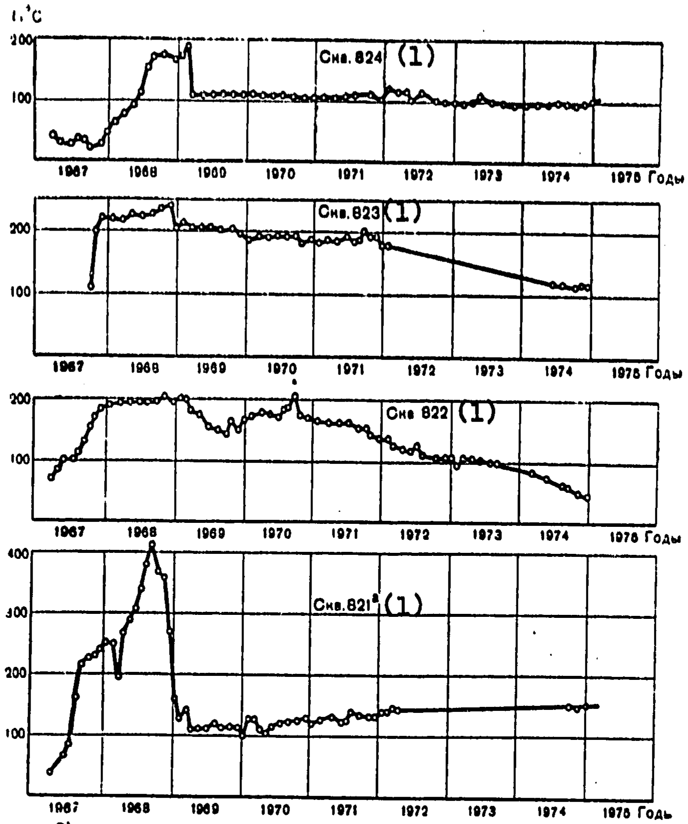

Figure 84. Change in bed temperature in observation wells in the first experimental section.
Key: 1. Well ...

In 1969 and 1970 there was a basic reduction in the bed temperature for all the observation wells in the first section: for wells 821a and 821 because the burned-out zone of the bed was cooled by the air injected into the bed after the combustion front passed through their bottoms, and for the other wells because of the reduction in the rate of air injection into well 804.

The yield rates of the individual wells in the western embayment of the Pavlova Gora field increased by a factor of 10-15 in comparison with their yield rates before the thermal effects were implemented.

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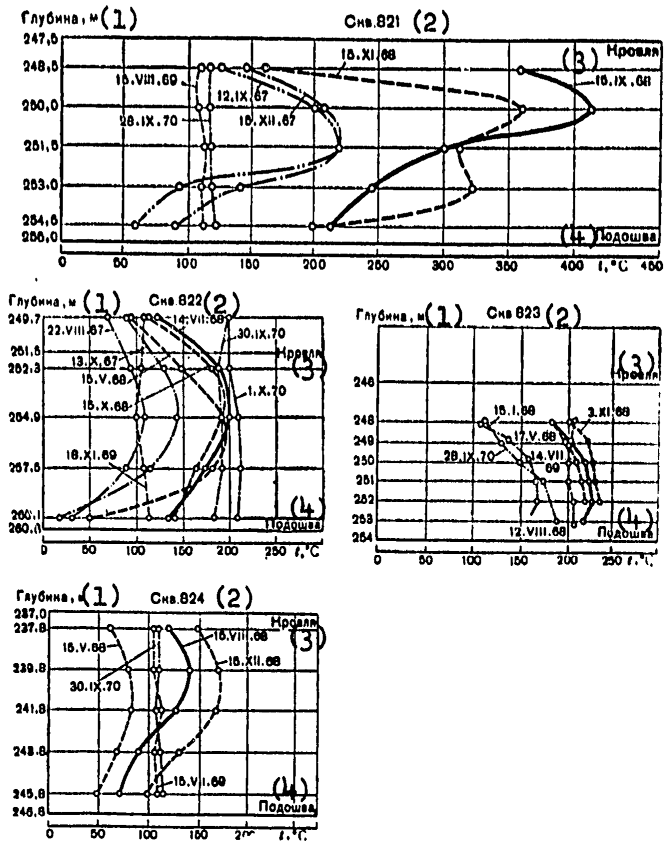

Figure 85. Change in temperature over the thickness of the bed in observation wells in the Pavlova Gora experimental section.

Key: 1. Depth, m
2. Well ...
3. Roof
4. Floor

As a result of the effect of the heat on the bed, oil extraction from the deposit increased by a factor of 4-5 (Figure 86).

The change in the oil's properties under bed conditions was related to the dissolution in it of gaseous combustion products (primarily CO_2), which lowered its viscosity and increased its volumetric coefficient.

There appeared to be no noticeable changes in the extracted oil's physical properties throughout the entire period.

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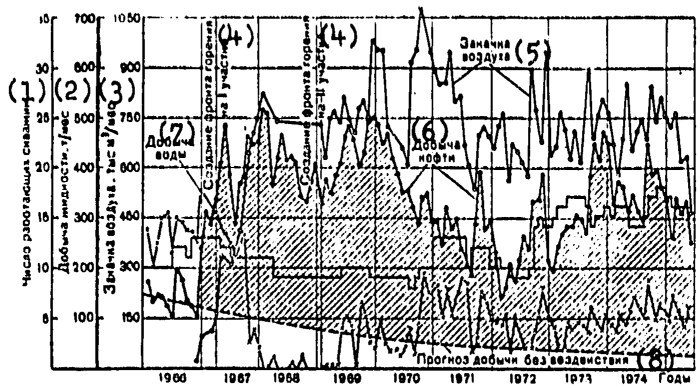

Figure 86. Indicators of the development of Pavlova Gora's western embayment.

Key:
1. Number of functioning wells
2. Liquid extraction, tons/month
3. Air injection, m^3 x x 1,000/month
4. Creation of combustion front in section ..
5. Injection of air
6. Extraction of oil
7. Extraction of water
8. Prediction of extraction without thermal action

The dimensions of the burned-out zones and the actual and critical densities of the air flow at the combustion front are evaluated by the following formulas.

1. Radius of the combustion front:

$$r_{CF} = \sqrt{\frac{\alpha_{uo} \sum Q_{AIR}}{\pi \alpha_{G} h q_{AIR} h_{эф}}}.$$

2. Actual density of the air flow at the combustion front:

$$u = \frac{Q_{AIR}}{2\pi r_{CF} \alpha_{g\,h} h}.$$

3. Critical density of the air flow (from the condition that the combustion front's rate of movement be maintained at a level no less than the minimally acceptable one, it is assumed that combustion stops if this condition is not observed):

$$u_{CRIT} = \frac{v_{min} q_{AIR}}{\alpha_{uo}}.$$

The following definitions are used in the formulas: ΣQ_{air} = = total amount of air injected, m^3/day; Q_{air} = amount of air injected, m^3/day; q_{air} = air consumed to burn out 1 m^3 of rock

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(350 m^3/m^3); h = effective oil-saturated thickness of the bed, m; $\alpha_{c.h}$ = coefficient of envelopment of bed by combustion, according to thickness (assumed to be 0.65); α_{uo} = coefficient of utilization of the oxygen in the air at the combustion front (assumed to be 0.18); v_{min} = minimum acceptable rate of movement of the combustion front (0.015 m/day for the first section, 0.03 m/day for the second).

At the end of 1972, the average radius of the burned-out zone in the first section was about 21 m, while for the second it was about 15 m, which has been confirmed by data gathered during geological investigations.

Calculations to determine the density of the air flow (assuming that the combustion front has a radial shape) indicate that since about 1970 the flow's density has been below the critical level. However, as a result of the uneven distribution of the air flow's density on the combustion front's outline in the first experimental section, there was unilateral movement of the front, in the shape of a tongue, in the direction of well 832. By the end of 1972 the combustion front was located in direct proximity to the bottom of this well, in view of which its operation was halted.

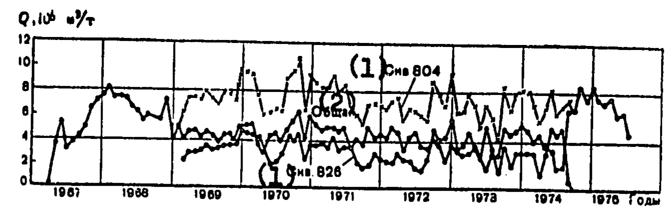

Figure 87. Dynamics of air injection in western embayment of Pavlova Gora oil field.
Key: 1. Well ... 2. Total

On the whole, the air injection rate for the first and second experimental sections was inadequate, because the compressor station did not provide the required amount of air (Figure 87). For normal development of the Pavlova Gora field using intrabed combustion, it would have been necessary to increase the compressor station's capacity to 100,000 m^3/day.

Attenuation of the process has been noticed in the direction of wells 831, 798, 797, and 824, and this has been confirmed by bed temperature measurements in observation wells (822, 823 and 824) and analyses of gas samples from these wells.

In the combustion attenuation zones, slow oxidation processes are taking place that contribute to stabilization of the

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temperature in the observation wells at 110-200°C for an extended period of time. Although the temperature in these wells increased in 1968 -- to 208°C in well 822, 240°C in well 823 and 189°C in well 824 (see Figure 85), caused by the approach of the condensation front -- since 1969 the temperature has dropped and remained at the following levels: 120-140°C in well 822, 200°C in well 823 and 110°C in well 824.

Development of the Deposit in Pavlova Gora's Western Embayment

The development of the deposit in the western embayment of Maykopskiy horizon 1 (second band) began in January 1959. The maximum oil extraction rate (470 tons/month) was reached by the end of the drilling period (1960). As early as the beginning of 1961, oil extraction had decreased 50 percent and was about 230 tons/month. By the beginning of the introduction of the intrabed combustion process (December 1966), the oil extraction rate was 110 tons/month.

During the 8-year initial period of development, 23,600 tons of oil were obtained, along with 9,100 m^3 of water and 910,000 m^3 of gas. The average gas factor was 38 m^3/ton. The bed pressure dropped from 10 kg/cm^2 to 7.5 kg/cm^2.

The original geological oil reserves in Pavlova Gora's western embayment were sufficient for the use of the intrabed combustion process. According to the calculations, the oil yield for the usual method of exploiting the deposit (to depletion) would have been about 30,500 tons by the time the profitability limit was reached (September 1977) and the final oil yield would have been 11.7 percent. By the beginning of the introduction of the intrabed combustion process, the current oil yield had reached 9.1 percent. According to the calculations, without the use of this process, by the end of 1974 the total amount of oil extracted would have been about 29,500 tons, for a current oil yield factor of 11.3 percent.

The use of intrabed combustion in the deposit in the period from 1967 to 1974 -- despite the low degree of bed involvement (two elements in the section out of the 10 that were planned) and the inadequate supply of air -- improved the basic development indicators significantly and had a comparatively large economic effect.

During the 8 years the process was in use, 33,718 tons of oil were extracted. This included 27,700 tons of additional oil, or 82 percent of the total extracted during this period.

From the beginning of the deposit's development to the end of 1974, the total amount of oil extracted was 57,306 tons, for a current oil yield factor of about 22 percent.

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Thus, the process made it possible to double the rate of deposit development. As early as the end of the second year, the total amount of oil extracted exceeded the maximum possible total expected if the deposit had been developed by the depletion method. With thermal action on the deposit, the current oil yield factor was 88 percent higher than its maximum possible value for the usual system of development. The current oil yield level at the end of 1974 was 430 tons/month; that is, it almost corresponded to the maximum extraction level achieved in the initial period of development, immediately after wells had been drilled in the entire deposit.

Below are some data on the additional extraction of oil, by years:

Year.	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
Extraction, tons x 1,000	3.4	3.9	4.3	3.7	2.6	2.4	3.4	3.0	3.5	3.5

From the data presented it is obvious that the effectiveness of the process changed from year to year, as far as the indicator "additional extraction of oil" is concerned. This indicator increased continually from 1967 to 1969, then decreased from 1969 to 1972, and began to rise again beginning with 1973. The change in the level of additional extraction is related to the state of the intrabed combustion process, the drilling of additional operating wells, and an improvement in the operating conditions. In the 1967-1969 period -- the initial stage of the experimental work -- there was active movement of the combustion front, accompanied by intensive displacement of the oil from the burned-out zones and a physicochemical effect exerted by the dissolved carbon dioxide.

In December 1968 in the first section and March 1970 in the second, the density of the air flow reached minimum values, at which the combustion process began to die out, and the effectiveness of the oil displacement began to drop. The improvement in this indicator in 1973-1974 was related to the introduction into operation of five new wells (drilled in 1972) and the improvement in well operation that was related to the successful implementation of measures to fight sand erosion (strengthening the sand by the coking method). As a result of these measures, the current oil yield level increased and reached 430 tons/ /month at the end of 1974. According to the factual data on the development of the deposit in the western embayment of Maykopskiy horizon 1 at the end of 1973, we see that the basic share (about 93 percent) of the total additional oil extracted was obtained from wells beyond the boundaries of the experimental sections. Of the total additional oil extracted by the end of 1973 (23,700 tons), the amounts obtained from sections 1 and

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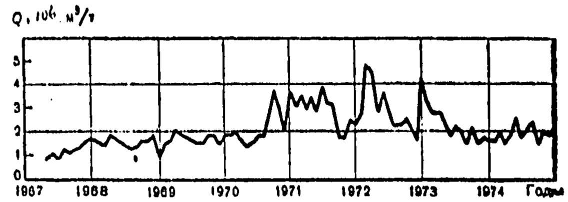

Figure 88. Change in air consumption rate per ton of extracted oil, by years.

2 were 1,480 and 1,390 tons, respectively. According to the plan, the additional amount of oil extracted from section 1 by the end of the experimental work should have reached 10,000 tons, for an oil yield coefficient of 0.546.

Thus, the use of the process in the two sections was reflected positively in the development of the entire site, which is explained by the physicochemical effect of carbon dioxide on the oil, as well as a slight increase in pressure in the deposit.

One important indicator of the process's effectiveness is the relative consumption of air per ton of additional oil extracted. By years, these data are shown below and in Figure 88:

Years.	1967	1968	1969	1970	1971	1972	1973	1974
Air consumption, m^3/ton	1546	2118	2183	2600	3523	3445	2384	2153

According to the technical plan for the experimental work, the average relative air consumption was 1,415 m^3/ton.

From the data that have been presented it is obvious that only during the first year of the process did the actual relative air consumption almost correspond to the projected figure, after which it began to increase and even in the period of active combustion (1967-1969) was higher than the projected figure by 50 percent or more. In the 1970-1972 period, the relative air consumption increased significantly and exceeded the planned figure by a factor of 1.8-2.6. The deviation of the actual relative air consumption from the projection was related to the use of oxygen at the combustion front and greater fuel formation than was provided for in the plan. In the 1970-1974 period, the increase in the relative consumption was related to the deterioration of the oil displacement mechanism because of an insufficient supply of air for the process.

Economic Effectiveness of the Intrabed Combustion Process

The additional capital investments for the process amounted to 369,000 rubles, including 104,400 rubles for the drilling of

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new wells in 1966 and 40,000 rubles for the same purpose in 1972.

Thanks to the high efficiency of the process, the expenditure recovery period was about 2.2 years.

The operating expenses for the process averaged about 140,000-145,000 rubles per year, including 42,000-45,000 rubles for the injection of air.

The production cost per ton of oil was almost 20 percent less than it would have been had the deposit been developed without the use of intrabed combustion. The total economic effect during the entire period the process was in use was several hundred thousand rubles, although its effectiveness decreased with time. For instance, during the period of the process's active phase (1967-1969), the annual effect was 18-20 percent, but in the later years it dropped to 7-10 percent a year.

On the basis of what has been written, the following conclusion can be drawn.

On the whole, the implementation of the project to encompass the oil deposit in the western embayment of Pavlova Gora by intrabed combustion was done at a high technical and economic level, but as a result of the low productivity of the compressor station, its more extensive development was retarded. The prospects for the development of the Pavlova Gora field are substantiated in a number of works put out by KrasnodarNIPIneft'. The total amount of oil extracted by use of the intrabed combustion method is 164,000 tons in the western embayment alone, as a result of which the final oil yield factor will approach 0.63 (when the deposit was developed by the depletion method, this figure was 0.11). There are also grounds for believing this method is promising for use in Pavlova Gora's eastern embayment.

In view of the fact that the active phases of the process have been completed in both the first and second sections, it is necessary to move on to the development of new sections, with due consideration for the utilization of the compressor station's productivity.

Strengthening the Bottom Zone of Wells by the Coking Method

During the development of individual oil deposits, the productive beds of which are composed of weakly cemented sandstones or unconsolidated sand, the problem of fighting sand erosion is one of particular importance. The presence of sand in the extracted oil means intensified wear of the intrawell and surface

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equipment, the formation of sand plugs, a reduction in the current oil yield, and breaks and even halts in well operation.

The restoration of well operation under such conditions is accompanied by considerable expenditures of facilities and labor to repair or replace equipment, flush or scrape out sand plugs, replace filter parts, drill second wells, and so on.

The fight against sand erosion is a serious problem when a deposit is being developed with the help of intrabed combustion or intensification of the inflow by cyclic steam injections. For instance, from the viewpoint of high economic effectiveness, it is advisable to use intrabed combustion at forced rates, bringing the duration of the development of individual sections (2-5 ha) down to 3-3.5 years, but this is difficult to do because of sand erosion. At the present time, the methods used to fight sand erosion include gravel or slot filters, reinforcing the wells with synthetic tars, and so forth. The most promising method for strengthening unconsolidated sand is coking.

Principles of Well Treatment Technology

The method of strengthening unconsolidated sand by coking consists of the following operations. Hot air is injected into the bed, as a result of which coke forms and becomes the cementing substance for the unconsolidated sand. In connection with this, rather high permeability of the treated bottom zone is achieved along with reliable strengthening of the sand. On the basis of investigations that have been carried out, it has been established that, when subjected to thermal treatment, oil containing 12-14 percent tar and asphaltenes is capable of forming coke that strengthens the sand. The strength of coked pieces from a core sample depends on the coke formation temperature and is evaluated according to its compression limit. The strength increases as the temperature does and reaches a maximum value of 120 kg/cm^2 at 360°C; a further increase in temperature leads to a reduction in strength. For instance, at 460°C a test piece becomes unconsolidated again. It has been established that after coking, the sand's permeability drops to 30 percent of its original value, while after strengthening with synthetic tars the decrease is only to 90 percent.

In order to strengthen the bed it is necessary to observe certain technological conditions:
1) rate of air injection;
2) rates of increase in the injected air's temperature and the maximum temperature;
3) duration of the treatment;
4) energy consumed.

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According to the data obtained during the strengthening of unconsolidated sand by coking in the Pavlova Gora field, it is recommended that air be injected at 900-1,000 m^3/day per meter of bed thickness.

During the first few days, the temperature of the injected air should be slowly raised to 300-350°C (at 10-15°C per hour). A temperature of about 300°C is maintained for almost the entire period of well treatment and is raised to 350-400°C only toward the end of the period. The duration of the process is determined either by the average thermal energy consumption per meter of bed thickness or by determining the moment of combustion front formation, which is established by a sharp change in the well's receptivity. The average value of the relative thermal energy consumption is about 0.5-1 million kcal/m.

Equipment Specifications

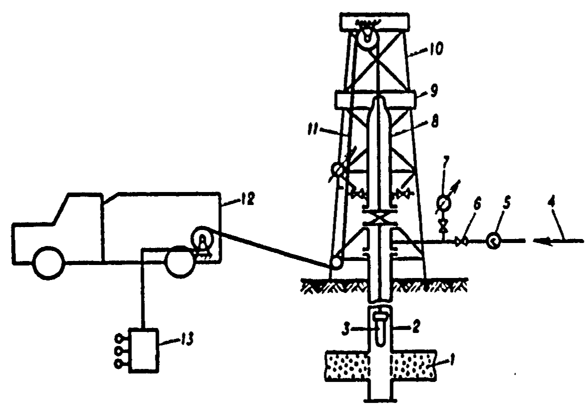

Figure 89. Arrangement of equipment during strengthening of a well's bottom zone by coking: 1. oil-bearing bed; 2. well; 3. electric heater; 4. air from compressor; 5. diaphragm-type flow meter; 6. gate valve; 7. manometer; 8. lubricator; 9. area for servicing lubricator gasket; 10. truncated derrick; 11. KTNG-10 cable; 12. hoist; 13. transformer.

During operations to strengthen the bottom zones of wells by coking, series-produced SUEPS-1200 electrothermal well treatment units can be the basic equipment used.

In order to provide for treatment of a well with air (in the absence of fixed compressor stations), it is possible to use portable UPK-80 or AKDS (consisting of two AVSh-3.7/200 compressors) compressors. Since the coking process proceeds

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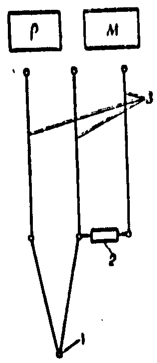

Figure 90. Plan for remote measurement of the temperature of the air injected into the bed: 1. thermoelectric junction; 2. thermometer; 3. signal cables; M = direct-current bridge; P = potentiometer.

continuously, it is better to have two compressors in order to insure an uninterrupted supply of air. For this reason the AKDS unit is more suitable for this work.

Figure 89 shows the arrangement of the equipment at the mouth of a well undergoing treatment by this method.

In order to seal the well and have the capability of raising and lowering the heater, it is necessary to install a well-mouth gate valve and a specially manufactured lubricator with a cable stuffing-box seal. In order to measure the injected air's flow rate, it is possible to use a type DP-430 flow meter. It is also necessary to have a series of instruments for measuring electrical value (megohmmeter, potentiometer). Remote measurement of the injected air's temperature can be accomplished with the layout shown in Figure 90.

After heating by the electric heater, the air's temperature can be calculated by the following equation:

$$t_A = \frac{860N}{VC} + 40°C,$$

where N = actual capacity of the electric heater, kw; V = air flow rate, m^3/hr; C = volumetric specific heat of the air, kcal/m^3/°C (with an average value of 0.3 kcal/m^3/°C).

Selecting Wells for Treatment by the Coking Method

Wells suitable for strengthening by the coking method can be those that are characterized by sand erosion, regardless of oil quality, bed thickness, depth of occurrence of the productive bed, formation pressure, and method of exploitation.

Actually, however, on the basis of the SUEPS-1200 unit's specifications (cross-section of the cable's power cores, quality of the electrical insulation and length of the cable, heater capacity), wells having the following characteristics are suitable for treatment:

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a) depth of occurrence of the productive bed -- up to 1,200 m;
b) operating column must be sealed;
c) diameter of the operating column -- 168 mm;
d) well-bottom static pressure must not exceed 60 percent of the operating pressure of the available air compressors;
e) a lack of significant cavities formed as the result of sand erosion, unless they can be filled with sand injected into the bottom zone.

When sand is injected into a bed, it is desirable to use the large-grained sand used for hydraulic mining.

Well Treatment Technology

Before unconsolidated sands are strengthened by the coking method, it is necessary to determine the coke-forming capability of the oil in the selected group of wells.

The silica gel tar content must be at least 10 percent, while the coke content must be at least 3-4 percent by weight.

When the oil's tar and coke contents are less than the given figures, it is necessary to inject oil satisfying this requirement into the well's bottom zone (over a radius of 1-1.5 m).

Preliminary injection of oil into the bottom zone is also advisable when there is a high degree of flooding of a well and the zone's degree of oil saturation may prove to be inadequate for the formation of a strong structure.

If much sand was extracted from a well during the preceding period of exploitation and a large cavity has formed, it is necessary to fill the cavity with sand before the strengthening operations begin. Considering this fact, it is advisable to strengthen a well by the coking method at an early stage of its operation.

Well Strengthening

Well strengthening is carried out in the following sequence.

1. Air injection at a rate of 900-1,000 m^3/day per meter of bed thickness.

2. Turning the heater on at 410-450 v.

3. Measuring the air temperature after heating and regulating it (by changing the voltage or the air flow rate). For 1-2 days the temperature should not exceed 250-300°C, after which it is raised to 350°C and kept there until the completion of the treatment.

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4. The duration of the treatment (in days) is first established approximately, on the basis of the heater's power and the average consumption of energy per meter of bed thickness, by the equation

$$\tau = \frac{Qh}{24\,880N},$$

where Q = assumed average thermal energy flow rate per meter of bed thickness, kcal/m; h = bed thickness, m; N = actual heater capacity, kw.

As experience is accumulated, the duration of the strengthening operation is defined more precisely.

In order to monitor the possible ignition of the bottom zone, it is necessary to make observations of the changes in the well's receptivity. The moment of ignition is established by an abrupt lowering of the receptivity.

5. As the treatment is completed, the heater is turned off and air injection ceases. The heater is raised into the lubricator. The lubricator is dismantled while the central gate valve is closed.

Well Development

The well development method affects the success of the treatments (the obtaining of additional oil). Because of the formation of highly viscous products of the oil's oxidation in a well's bottom zone, it is possible that the well's productivity can be reduced. Therefore, one of the goals of well development operations must be to insure the elimination of viscous products that form. This can be achieved in the following manner.

1. Drainage of the bottom zone immediately after completion of the treatment. In connection with this and because of the presence of a high-temperature zone, the oxidized products' viscosity is lowered, resulting in some cleaning of the well's filter. Reducing the pressure through the connecting pipe limits the rate of increase of the depression on the bed, which prevents filter damage. The pressure is reduced until there is no more gas escaping.

2. Repeated, more significant heating (in a radial direction) of the bottom zone by the cyclic injection of steam (up to 1,000 m^3 of steam per meter of bed thickness).

3. The use of effective solvents of asphalt and tarry substances.

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4. The injection of oil into the well (double or triple the volume of the well shaft).

As one of these well development operations is completed, deep-pumping equipment is lowered into the well and it is put into operation.

Basic Results of Work on Strengthening Unconsolidated Sand by the Coking Method

During a 3-year period, 17 well treatments were performed in the Pavlova Gora oil field, as a result of which the total increase in the additional extraction of oil was about 1,800 tons.

The best results were obtained from wells 797a, 843, 834, and 831. Nine wells in the basic field of the deposit in Pavlova Gora's western embayment were treated, out of a total of 19 operating wells. Double treatments were administered to 5 wells and triple treatments to 3, which amounts to 55 and 33 percent, respectively, of the total number of wells treated. Repetition of the treatments was the result of a lack of sufficient experience in the technology of performing the work, as well as a number of reasons unrelated to the technology (cessation of the operation because of an interruption in the supply of air, formation of plugs and appearance of foreign objects in the filter section).

The success of the treatments (as estimated by the increase in additional oil extraction) was 94 percent for the 3-year period, which characterizes this method of strengthening unconcolidated sand as extremely effective in comparison with the other methods that are known, such as strengthening with various synthetic tars, and so forth.

The duration of the period of effective operation of individual wells after treatment (as of 1 October 1974) was:

Time of operation, well-months.	26	17	15	12	6	6
Number of wells. . . .	1	1	1	2	2	7

The maximum period of effective operation (more than 2 years) was seen for well 797a, while the average length of the period was 9 months. If we eliminate from the analysis the well treatments performed during the initial period (imperfection of the technology and lack of experience, for example, for well 797a from August 1971), as well as those interrupted for technical reasons or reasons related to complications in the filter section (wells 831 and 798, for example), the average duration of the period of effective operation increases to 21 well-months.

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Table 34. Data on Industrial Test of

Номер скважины (1)	Дата обработок (2)			Продолжительность эффективного периода эксплуатации после обработки, месяцы (6)	Показатели обработки (7)		
	первая (3)	вторая (4)	третья (5)		расход песка, т (8)	средний расход воздуха, м³/сут (9)	средняя температура, °С (10)
797а	VIII 1971 г.	—	—	4	—	6000	250
797а	—	VIII 1972 г.	—	20	5,0	4200	350
831	IX 1972 г.	—	—	2,5	—	3100	350
798	XI 1972 г.	—	—	2,0	10,0	3600	340
808	I 1973 г.	—	—	—	10,0	4500	280
708	—	II 1973 г.	—	15	10,0	4500	350
843	IV 1973 г.	—	—	17ж	5,0	4500	350
831	—	VIII 1973 г.	—	5	5,0	4700	350
833	IX 1973 г.	—	—	12	7,0	4800	340
834	X 1973 г.	—	—	12ж	10,0	5400	350°
820	XII 1973 г.	—	—	5	10,0	5100	260°
831	—	—	II—III 1974 г.	6ж	10,0	4300	330°
807	III 1974 г.	—	—	6ж	10,0	6600	200°
808	—	—	VI 1974 г.	3ж	10,0	4200	300°
820	—	VI 1974 г.	—	3ж	10,0	5000	320
798	—	—	VIII 1974 г.	1ж	10,0	5500	270
833	—	IX 1974 г.	—	—	10,0	4200	350
Итого (25)	9 скважин (26)	5 скважин (26)	3 скважины (26)				

Key:

1. Well number
2. Date of treatments
3. First
4. Second
5. Third
6. Duration of effective period of operation after treatment, months
7. Treatment indicators
8. Sand consumption, tons
9. Average air consumption, m^3/day
10. Average temperature, °C
11. Method of development
12. Injection of cooled liquid
13. Injection of solvent
14. Reduction of pressure
15. Additional oil extracted during effective operation period, tons x 1,000
16. Notes
17. Nonoperational before treatment
18. Well continues to operate
19. Foreign objects discovered in well bottom
20. Treatment was halted because of compressor
21. Treatment ineffective
22. Treatment had little effect
23. Treatment effective
24. Results positive
25. Total
26. . wells

The effectiveness of the well treatments was affected to a considerable extent by such parameters as the temperature of the injected air and the amount of heat introduced into the bed, which is obvious from Table 34.

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Strengthening Unconsolidated Sand by Coking

Метод освоения (11)			Дополнительная добыча нефти за эффективный период эксплуатации, тыс. т (15)	Примечание (16)
(12) закачка охлажденной жидкости	(13) закачка растворителя	(14) снижение давления		
+	−	−	99	До обработки бездействовала (17)
+	−	−	707	Скважина продолжает работать (18)
+	−	−	43,0	На забое обнаружены посторонние предметы (19)
+	−	−	55	Обработка была прервана из-за компрессора (20)
+	−	−	−	Обработка неэффективна (21)
−	−	+	41	Малоэффективная обработка (22)
−	−	+	355	Обработка эффективна (23)
−	−	+	25	Обработка малоэффективна (22)
−	−	+	70	Обработка малоэффективна (22)
−	−	+	125	Обработка эффективна (23)
−	−	+	60	Обработка малоэффективна (22)
−	+	−	130	Обработка эффективна (23)
−	−	+	60	Обработка малоэффективна (22)
+	−	−	55	Обработка малоэффективна (22)
+	−	−	32	Обработка малоэффективна (22)
+	−	−	−	Результаты положительные (24)
+	−	−	−	Результаты положительные (24)
			1845	

The most successful results correspond to the higher injected air temperatures and the higher specific thermal energy consumption rates per meter of thickness (wells 797a, 843, 834). For these wells the air temperature was about 350°C, while the specific energy consumption was 0.7-2.0 million kcal/m.

An analysis of the data on the series of wells treated in 1974 shows that the air temperature was 200-326°C, while the specific thermal energy consumption rate was 0.5-1.0 million kcal/m. It is obvious that this deviation from the previously indicated optimum temperature values had a negative effect on the effectiveness of the treatments. It is necessary to carry out the treatments at temperatures of no less than 350°C and a specific energy consumption rate of 1 million kcal/m.

Intrabed Combustion Under Conditions of the Simultaneous Occurrence of Macro- and Microporous Reservoirs in the Zybza Field

The second site for the use of intrabed combustion on a bed was chosen in 1964: lens 4 of the Sarmatian horizon of the heavy oil deposit in the Zybza-Glubokiy Yar field. The productive bed is characterized by nonuniformity of the reservoir properties, both vertically and horizontally. The reservoir consists of interlayers of clays, aleurites and dolomitic and clay

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breccia or coarsely fissured breccia with a permeability of 0.5-1 or more. The oil reservoir consists of oil-saturated fissures and pores in the rock or voids formed by the breccia.

The following figures are a description of the oil, data on the lens, and several parameters utilized in the technological plan:

Lens area, ha	6.7
Average depth of occurrence of bed, m	660
Average thickness, m.	5.7
Current degree of oil saturation of the bed, %.	42.1
Bed temperature, °C	29
Oil density, g/cm³.	0.976
Bed oil viscosity, cp	2,000
Atomic ratio (H/C).	1,586
Content of tars containing sulfuric acid, %	64
Fuel consumption (coke residue), kg/m³.	39.4
Air consumption per cubic meter of rock, m³/m³.	425

The experimental industrial work on thermal action on a bed consisting of a complicated reservoir was performed because there are other deposits of this type in Krasnodarskiy Kray aside from the Zybza one.

According to the technological plan, a linear form of thermal action on the bed was stipulated for this site. Three injection wells were located on the short axis in the central part of the lens, at a distance of 70 m from each other, while the development of the combustion front on the two sides of the lens was at depths of 130 and 230 m. On both sides of the injection well line there was a single observation well, for the purpose of monitoring the process; this is shown in Figure 91.

The lens was penetrated by 18 wells. The bed within the lens is characterized by a large degree of nonuniformity and instability of the reservoir properties. In a small area of lens 4, the horizon is revealed by some wells to be highly permeable, while in other (neighboring) wells it is even difficult to delineate the horizon occurrence interval. Moreover, one of the injection wells (1H) did not, in general, penetrate the oil-bearing bed, but went into the tapering-out zone. The lens is tilted: the difference in the absolute depths at the end points along the lens's long axis is 100 m.

For the plan, it was assumed that the lens is a single object. As the experimental work proceeded, however, the lens's structure and boundaries were determined more precisely. From the results of air injection into the individual wells, it was possible to establish the boundaries, even though this was done on

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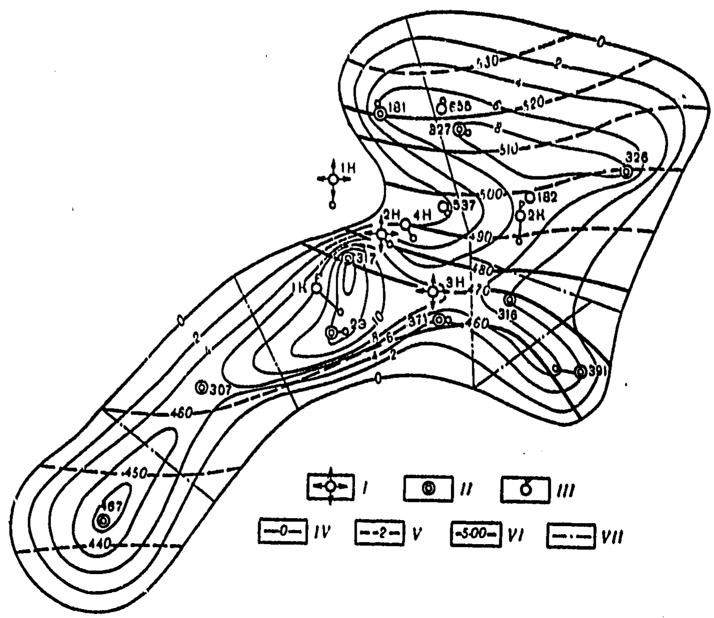

Figure 91. Structural diagram of the roof of lens 4 of the Sarmatian horizon and map of uniform thicknesses: I. injection wells; II. operating wells; III. observation wells; IV. boundary of tapering out of lens; V. isohypses along roof of lens; VI. lines of uniform thicknesses; VII. boundaries of separate sections.

an extremely provisional basis, of a number of mutually isolated sections that are shown in Figure 91. The central part of the lens (the area of wells 2H, 3H, 4H, 181, 371, 2E, 1K, and 317, where the work to initiate combustion was done in 1971 and 1972) is characterized by heavy fissuring and does not contain any free, mobile oil. Free movement of air from the injection to the operating wells took place along the fissure ducts. In addition to the strongly developed fissuring, this part of the lens lacked a sufficient quantity of oil, which was determined by injecting steam (1,852 and 1,460 tons) into operating wells 2E and 317, which reacted to the injection of air into well 3H. After the injection of this amount of steam into these wells, no oil or water was obtained from them when they were drained.

In the experimental section in the central part of the lens, several attempts were made to implement the combustion process with the help of a bottomset burner. The attempts to initiate combustion in the bed through wells 2H and 3H, with the help of

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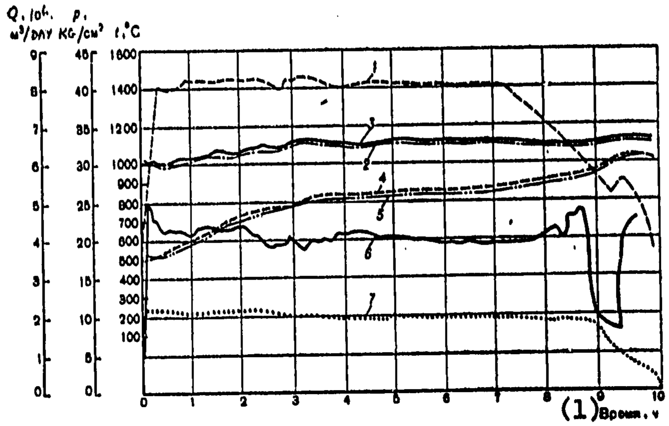

Figure 92. Change in pressure, air flow rate and temperature, with respect to time, during operation of bottomset gas burner: 1. air flow rate between 65- and 127-mm columns; 2. pressure in ladder; 3. pressure between 127- and 203-mm columns; 4. pressure between 65- and 127-mm columns; 5. pressure in 38-mm column; 6. temperature of waste gasses in burner; 7. flow rate of air for combustion in 38-mm column.
Key: 1. Time, hrs

a bottomset gas burner designed by KF VNII, were not successful. Every time there was a decrease in the injection well's receptivity 3-10 hrs after the bottomset gas burner began to operate. The gas consumption rate was 240 m^3/day, while about 12,000 m^3/day of air was suppled to burn the gas and cool the burner. The change in the parameters for one of the stages of combustion process implementation is shown in Figure 92.

For normal operation of the gas burner it is necessary to keep its operating conditions constant by supplying it with air. Because of the drop in the well's receptivity, in order to insure operation of the gas burner it was necessary to increase the pressure of the injected air so as to maintain the present air flow rate of about 12,000 m^3/day. The pressure at the well mouth was gradually increased to 35 kg/cm^2 (the maximum pressure the compressor station could provide), after which the flow rate of the air injected into the well dropped and the gas burner stopped operating.

One of the reasons for the decrease in the injection well's receptivity was thermal expansion of the rock in the bed, which led to the closing of the fissures that were the lines of communication in the bed. It should be mentioned that the

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bottomset gas burner was not provided with automatic temperature control facilities, so the temperature had increased considerably by the time it stopped working.

As a result of the reduction in the wells' receptivity and the significant curtailment of the discharge of heat directly into the bed, there was a sharp increase in the temperature at the bottom of the well. The wells' receptivity was not restored after the bottom zones were cooled. Only after treatment of a well's bottom zone with a mixture of hydrochloric and hydrofluoric acids was the rock melted and the receptivity restored. Subsequent attempts to ignite the bed with the help of a gas burner led to a reduction in well receptivity.

An experimental installation in a laboratory was used to conduct experiments on a nonuniform porous medium, consisting of sand and breccia, in order to study the mechanism of the intrabed combustion process and determine the basic operating parameters that were applicable to the bed in the Zybza field.

As a result of these experiments, the following basic regularities were established.

1. Oil combustion in rock consisting of breccia takes place with high consumption of air and a lower combustion front propagation rate in comparison with the process in a porous medium consisting of sand.

2. The quantity and size of the inclusions of a nonporous mass have a substantial effect on the combustion process in a nonuniform porous medium.

3. Flooding of the porous medium causes the combustion conditions to deteriorate.

An analysis of the causes of unsuccessful initiation of the combustion front in the experimental section of the Zybza field with the help of the bottomset gas burner, as well as an additional study of the combustion process on a linear model that allows for the bed's nonuniformity, led to the conclusion that it is necessary to have a more careful preliminary preparation of the injection well and that another method of creating the combustion front should be used.

Considering the nature of the reservoirs' structure, the bed's filtration properties, and the lack of oil in injection well 3H, this well received an injection of 50 m^3 of waterless heavy oil heated to a temperature of 80°C. After 2 days, the height of the column of oil above the bed had increased to 20 m.

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Bottomset gas burners are most suitable for thick productive beds (at least 15 m thick) containing immobile but easily oxidizable oil. When the gaseous heat carrier's temperature is high (530-820°C) and the air flow is very dense (at the initial moment of initiation of combustion), there is a reduction in the oil content below the amount minimally necessary for the successful creation and development of a combustion front. For our case, where the bed's effective thickness is about 5.5 m, an electric heater is more suitable because it makes it possible to raise the injected air's temperature slowly (10-100°C) while keeping the air flow's density low. The temperature's rate of increase is controlled by regulating the working voltage (380-560 v), while the air flow's density is controlled by regulating the injection rate. In order to generate a combustion front it is necessary to provide a heat air temperature on the order of 320-420°C. In order to achieve successful ignition of the bed, the total amount of heat introduced into it is of great importance. According to foreign data, a heat consumption rate on the order of 0.25-2.75 million kcal per meter of bed thickness is recommended.

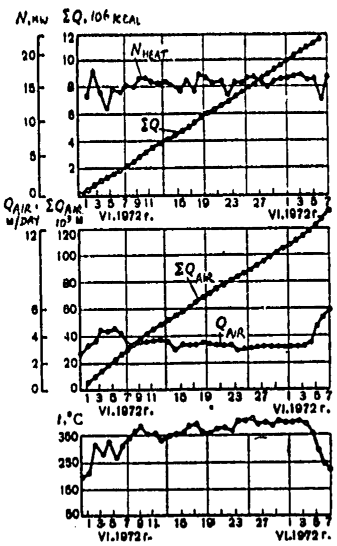

Figure 93. Technological parameters of the combustion initiation process in well 3H.

The electric heater for creating the combustion front consisted of the following elements: a three-phase heater with a rated capacity of 24 kw (length -- 5.5 m, diameter -- 116 mm); a type KTNG-10 power cable; a TEKh50v-13AZ control station; an ATS 3-30 autotransformer.

In order to monitor the temperature of the air injected into the bed, the heater was fitted with an KhK thermocouple and a thermistor. The well mouth was sealed with a lubricator. The combustion initiation process was begun on 31 May 1972 and continued until 7 July 1972. The technological parameters of the combustion initiation process are shown in Figure 93. The air consumption rate was about 3,500 m^3/day at a temperature of 350-400°C, and the well-bottom capacity of the electric heater was maintained at a level of 15 kw. A total of 11.5 million kcal of thermal energy

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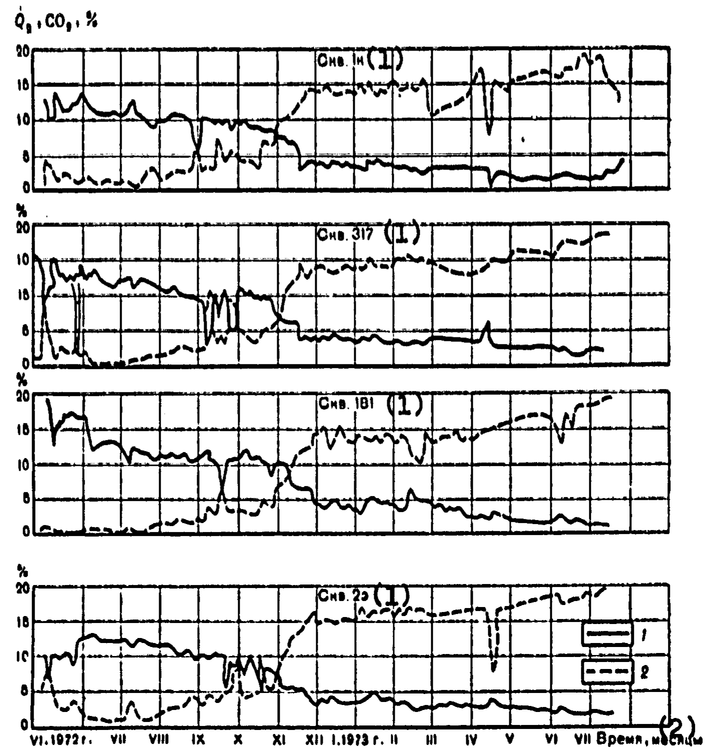

Figure 94. Change in carbon dioxide (1) and oxygen (2) contents in extracted gas.
Key: 1. Well ... 2. Time, months

and 135,000 m^3 of air was introduced. The specific heat consumption rate was about 2 million kcal/m. An analysis of gas from the wells led to the conclusion that the combustion front was created 10-15 days after the beginning of the process. The electric heater was operated for a period of 36 days in order to implement the successful development of a combustion front by creating a more extensive zone of high temperatures around the injection well. Calculations show that by the moment of combustion front generation, the bed was heated to 320°C over a radial distance of about 1 m. After the electric heater was turned off, the air flow rate was gradually increased from 3,000 to 19,000 m^3/day over a period of 23 days. The pressure was raised from 1.7 to 25 kg/cm^2.

From the beginning of the creation of the combustion front (15 May 1972) to the end of November, combustion proceeded normally,

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with a very small increase in the waste gas's O_2 content (from 0 to 2-5 percent) and a drop in the CO_2 content from 12-15 to 8-10 percent, accompanied by constant air injection and maintenance of the pressure at one level, as shown in the graphs in Figure 94.

Beginning with the end of November, the O_2 content began to increase from 4-5 to 14-15 percent and the CO_2 content dropped from 8-10 to 3-4 percent, although the air flow rate and pressure remained constant.

In order to maintain the combustion process, air injection was reduced from 21,000-22,000 to 11,000-12,000 m^3/day, which led to a decrease in the pressure to 12 kg/cm^2. As a result, over a period of 4 months there was a very slow increase in the gas's O_2 content and a similar decrease in its CO_2 content. By August 1973, air injection into well 3H had ceased, since the O_2 content had risen to 18-19 percent and the CO_2 had dropped to 1.5-2 percent. This indicated that only low-temperature oxidation of the oil was taking place in the lens.

From the beginning of the experimental work, there was almost no increase in oil extraction from the operating wells as a result of the intrabed combustion process.

As a result of the work done in the experimental section from 1970 to 1973, it was established that the lens's boundaries and the thickness and degree of oil saturation of the bed are substantially different from those mentioned in the development plan. The site does not correspond to the previously existing representations, and the conditions for conducting an experiment in implementing intrabed combustion were extremely unfavorable.

The following basic conclusions can be stated.

1. The implementation of the VG process in deposits of heavy, high-viscosity oils in fracture-type reservoirs is characterized by considerable complexity, both in the early period of combustion initiation and in the subsequent period of regulation of the combustion front's movement.

2. The basic reason for the complexity of the implementation of the process is nonuniformity of the reservoir's physical properties (porosity, permeability, degree of saturation with gas, oil and water, thermal properties).

3. The negative results obtained when the VG method was used under macro- and microporous reservoir conditions are of

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definite scientific value and must be taken into consideration when selecting a method of thermal action on a bed, allowing for the physical and geological peculiarities of the oil-saturated reservoir.

4. In beds that are fracture-type reservoirs, when the residual oil saturation of the injection well's bottom zone is inadequate for the formation of the necessary concentration of fuel, it is possible to create a combustion front with the help of an electric heater. In order to do this, it is necessary to inject a small amount of heavy oil into the bed.

5. The presence of a developed system of fissures and an inadequate degree of saturation with liquid led to the rapid appearance of breakthroughs of injected air into the wells.

6. The experimental work done at this site yielded negative results and almost no increase in output was obtained, despite the fact that the normal combustion process lasted for almost 5 months.

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CONCLUSION

[Text] Experimental industrial projects in the exertion of a thermal effect on oil-bearing beds, which were first conducted in the oil fields of Krasnodarskiy Kray and then in other parts of the country, demonstrated the high degree of effectiveness of this method as a means for insuring a high level of exploitation of oil-saturated reservoirs.

In the course of this work, various technological processes for exerting a thermal effect on a bed were tested for use under specific physical and geological conditions, along with the equipment used to implement the process.

The results of the theoretical research and the experimental industrial work in the area of thermal action on the bed and the bottom zones of wells confirm the possibility of their practical introduction, on a large scale, as a means for the more nearly complete exploitation of a bed.

The experimental industrial work in this field, alone, made it possible to extract about 6 million tons of additional oil, with an economic savings of more than 30 million rubles.

The research data can be used by scientific research and planning institutes to draw up technological plans for developing deposits with the help of various thermal processes, such as cyclic-block steam action on a bed, oil displacement with heat carriers in combination with cold water (the method of creating thermal fringes), wet intrabed combustion, and others.

The further development of projects concerning the problem of improving the utilization of high-viscosity oil resources in the Urals-Volga, Western Siberia and Western Kazakhstan provinces, as well as areas of the Komi ASSR, Azerbaydzhan, the North Caucasus, and Northern Sakhalin Island is the result of the use of thermal methods for developing oil deposits.

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It should be mentioned that the development of thermal processes for acting on an oil-bearing bed is related to the complexity and diversity of the technical and technological problems encountered, which may be solved by enlisting the aid of many branches of industry, scientific research and planning and design organizations, and institutes subordinate to the USSR Academy of Sciences.

Considering the great national economic importance of the problem of increasing the oil yield of beds in the Tenth Five-Year Plan (and subsequent ones), a program of integrated measures aimed at increasing the degree of extraction of oil from the bowels of the Earth is now being prepared. This program concerns not only the Ministry of the Petroleum Industry, but also allied branches of industry (Ministry of the Petroleum Refining and Petrochemical Industry, Ministry of the Chemical Industry, Ministry of Chemical and Petroleum Machine Building, Ministry of the Electrical Equipment Industry, Ministry of Heavy and Transport Machine Building, Ministry of the Electronics Industry, and Ministry of the Chemical Instruments Industry) that are responsible for the creation of special equipment, instruments and chemical products for the purpose of both improving the existing methods of affecting a bed and creating new processes to increase oil yield.

In particular, this program provides for the solution of a number of scientific and technical problems, with primary emphasis on the organization of the series production of special equipment to support the use of thermal methods for developing oil deposits, for which purpose both material and financial means have been allocated.

It has been suggested that during the Tenth Five-Year Plan a base be created for the widespread introduction of thermal methods in combination with thermochemical and other methods, for the purpose of obtaining higher oil yields.

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